NASA Technical Memorandum 80137

# ORBIT DESIGN FOR SOLAR AND DUAL SATELLITE OCCULTATION MEASUREMENTS OF ATMOSPHERIC CONSTITUENTS

NASA-TM-80137 19790023075



David R. Brooks
Edwin F. Harrison

July 1979



NASA

National Aeronautics and
Space Administration

**Langley Research Center**
Hampton, Virginia 23665

## INTRODUCTION

A growing appreciation of the need for monitoring and understanding the Earth's atmosphere on a global scale has led naturally to examination of various satellite-based techniques for establishing a global measurement capability which cannot readily be achieved with ground-based systems. Typical atmospheric constituents of interest include stratospheric ozone, aerosols, nitrogen oxides, and halogen compounds. The basic measurement desired is a vertical profile through part or all of the atmosphere. One strategy for making atmospheric profile measurements is to use the occultation mode, in which a detector satellite follows the passage of some energy source as it rises or sets on the Earth's horizon relative to the detector. As the line of sight between source and detector passes through the atmosphere, measurements as a function of altitude of the sight line relative to the local surface are obtained. Such data may be manipulated mathematically, at least in principle, to obtain local vertical profiles and other quantities of interest, like integrated column totals.

Two possible energy sources are immediately apparent. First, the Sun provides a strong source which can be exploited to provide vertical profiles as it rises or sets relative to a detector satellite (ref. 1). Advantages of using the Sun include the presence of a strong signal over a wide spectral band and (as will be shown) a regular longitude-latitude coverage pattern which lends itself to certain types of global monitoring activities. The readily apparent major disadvantage is the restriction of measurements to local dawn or dusk (no determination of diurnal variations in the measured quality), and a lack of control over the coverage geometry, especially on short missions (a week or two, for example). An alternative source is a laser which may be aboard a second satellite or on the detector satellite, to be reflected from a passive second satellite. This system has the advantage of using a controlled point source of energy with high spectral selectivity (a potential advantage especially when direct detection is used). There is more control over spatial and temporal coverage, with the possibility of obtaining diurnal variations which are fundamentally inaccessible when the Sun is used as a source. Possible disadvantages include the cost of two separate systems, high sensitivity to orbital variations, and power restrictions on the laser sources, especially in the reflected mode of operation.

Orbit design criteria for both solar and dual satellite occultation missions are described in this paper. The goal is to arrive at and study in detail some orbit configurations which illustrate the available output of representative missions. An attempt is made to present results from each type of mission on a consistent basis so that temporal and spatial coverage of each approach can be compared. Of particular interest for global modeling of atmospheric distributions are the longitude-latitude and latitude-time coverage patterns. For solar occultation, the basic features of these patterns may be understood in terms of the Sun's apparent motion around the Earth and the rotation of the satellite orbital plane relative to an inertial framework, as driven by the Earth's non-spherically-symmetric gravitational field. In the dual satellite case, the approach selected here as being the most interesting and having the greatest potential practical value for long-term missions involves relating the orbital plane precessions and periods in such a way as to define repetitive coverage patterns which can be controlled over long periods of time.

In the next section, the required basics of satellite motion are summarized. Then, results are presented for long-term simulated solar occultation and dual satellite missions. The advantages, disadvantages, and implications of each type of mission are discussed from the point of view of using the available data as input to regional or global atmospheric models. An example of some cursory statistical data analysis is given for the solar occultation case.

Two short precursor missions are proposed to demonstrate the feasibility of each of the two approaches to occultation measurements. For the solar occultation case, there is no reason why the short mission cannot be a "piece" out of the long mission, with the resulting spatial coverage being determined by the season and time of day of the orbit injection. For the dual satellite case, the precursor mission could involve a simple coplanar geometry wherein the transmitter or reflector, as the case may be, is just moved over the horizon from the detector. Then, there would be no attempt to obtain large amounts of spatial coverage, but only to perform a verification test for the technical aspects of the measurement system. It is also possible that some measurements of trace constituents which require long instrument integration times might be possible on this mission, but not on the long-term mission.

## THE DYNAMICS OF SATELLITE MOTION

The usual Keplerian approach to orbit dynamics must be modified to encompass the problems of interest here (ref. 2). Due to the well-known fact that the Earth is not spherical, but roughly an oblate spheroid, the right ascension of the ascending node of an orbit and the argument of its perigee are not fixed in inertial space, but precess as follows:

$$\dot{\Omega} = -\frac{3}{2} J_2 \frac{r_\oplus^2}{p^2} \dot{M} \cos i \qquad (1)$$

$$\dot{\omega} = \frac{3}{2} J_2 \frac{r_\oplus}{p^2} \dot{M} (2 - 2.5 \sin^2 i) \qquad (2)$$

$$\frac{3}{2} J_2 = 1.6238235 \times 10^{-3}$$

$r_\oplus$ = 6378.145 km

$\dot{M}$ = mean motion (deg/day, for example)

$p = a(1 - e^2)$, km

$i$ = inclination, deg

where $\dot{\Omega}$ is the precession rate of the right ascension of the ascending node and $\dot{\omega}$ is the precession rate of the argument of the perigee, with units consistent with the way in which the mean motion $\dot{M}$ is expressed. For the most part, the orbits of interest for Earth monitoring are at least nominally circular, so that the location of the perigee is apparently arbitrary. However, the perigee precession is important even for circular orbits, as it affects the definition of an orbital period and consequently the mean motion $\dot{M}$ in equations (1) and (2). For the present purposes, the period of interest is not the perigee-to-perigee period (anomalistic period), but the nodal period $\tau_N$, which is the one an observer at fixed latitude will deduce for an orbiting object as he measures time between overhead passages of the object across his latitude. This value differs from the Keplerian period only by a few seconds, but it is a quantity which must be taken into account in assessing long-term orbital behavior.

The nodal period is best defined in terms of the mean motion $\dot{M}$, which according to this first order perturbation theory, is given by:

$$\dot{M}_o = 2\pi/\tau_o \text{ rad/sec} \qquad (3)$$

$$\tau_o = 2\pi a\sqrt{a/\mu} \text{ sec } (\mu = 398601.2 \text{ km}^3/\text{sec}^2) \qquad (4)$$

$$\dot{M} = \dot{M}_o[1 + \frac{3}{2} J_2(r_\oplus{}^2/p^2\sqrt{1 - e^2} (1 - \frac{3}{2} \sin^2 i)] \qquad (5)$$

Then, the nodal period is:

$$\tau_N = 2\pi/(\dot{M} + \dot{\omega}) \qquad (6)$$

As an example, a $50^o$, 600 km circular orbit has the following quantities associated with it:

| | | | |
|---|---|---|---|
| $a$ | = 6978.145 km | $\dot{M}$ | = 5362.49 deg/day |
| $\tau_o$ | = 5801.2 sec | $\dot{\omega}$ | = 3.877 deg/day |
| $\tau_N$ | = 5796.1 sec | $\dot{\Omega}$ | = -4.676 deg/day |

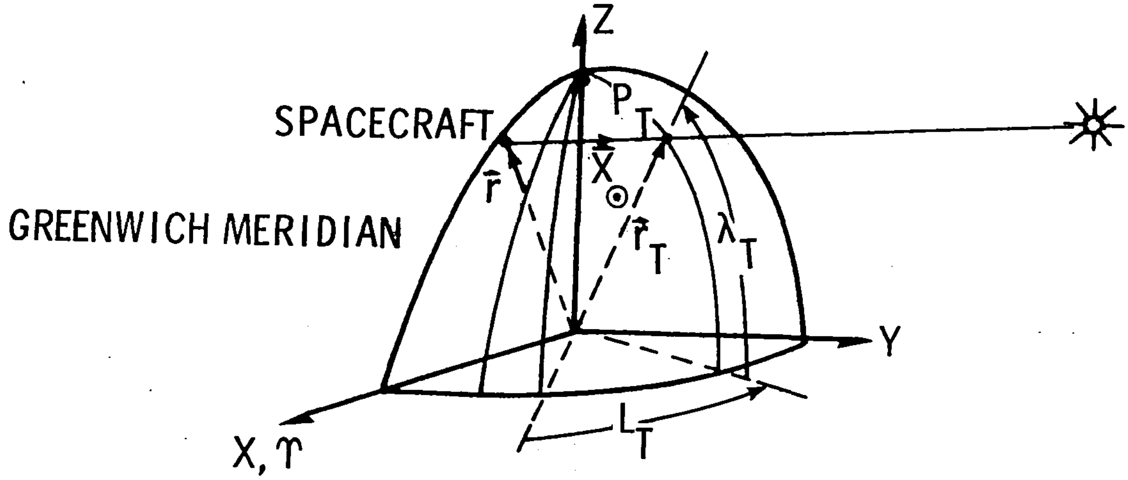
In this example, the orbit plane will precess through $360^o$ of inertial space in 76.99 days. This is of interest in relation to the Sun's apparent precession which is, on the average, 0.9856473 deg/day. Thus, the average precession rate of the satellite plane relative to the Sun is -5.662 deg/day, so that the orbit plane precesses through $360^o$ relative to the Sun in 63.58 days.

The generation of satellite orbits for this analysis has been done with appropriate modifications to a general-purpose orbit propagation program developed at Langley Research Center for Earth-orbiting mission analysis (TRACK 2). The program is based on first-order perturbation theory and produces a variety of printed and graphic output for studying the average long-term behavior of Earth orbiting satellites.

SOLAR OCCULTATION MISSIONS

The orbit geometry for characterizing a solar occultation mission is defined in sketch 1.

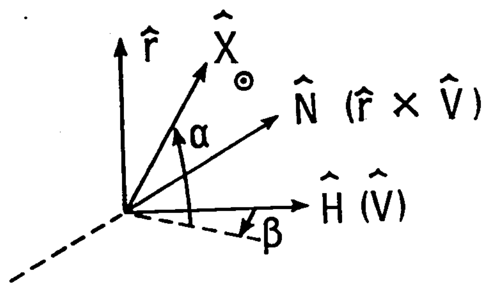
Sketch 1. Orbit geometry for a sunrise or set.




All the vectors are expressed in a right ascension-declination system, which is an Earth equatorial system with x-axis fixed in inertial space and pointed in the direction of the Vernal Equinox vector (♈). The unit vector $\hat{x}_\odot$ points from the spacecraft to the center of the Sun. A sunrise or set occurs, by definition, at that instant at which the projection of $\hat{x}_\odot$ is tangent to the surface of a fictitious spherical Earth at $P_T$; the position vector to $P_T$ is $\vec{r}_T$, with longitude and latitude coordinates $L_T$ and $\lambda_T$. Note that the maximum latitude of the tangent point can exceed the maximum sub-satellite latitude and that the location of the tangent point depends simultaneously on the orbit inclination and altitude, solar position, and time. It is useful to think of the tangent latitude as depending predominantly on the orbit parameters and the sub-solar declination, and the tangent longitude as being determined largely by the Earth's rotation. Thus, it is expected that the tangent latitude will undergo a relatively slow variation as the Sun's declination changes and the orbital plane precesses, while the Earth's rotation, being much faster and independent of these two effects, will produce much more rapid variation in the tangent longitude. Consider the angular rates involved: relative to an inertial coordinate system, the Sun appears to precess at about 1 deg/day in the positive direction, and orbit of less than 90° inclination precesses in the negative direction at a rate of as much as several degrees per day (recall the example from the preceding section), while the Earth rotates in the positive direction at about 361 deg/day.

The unit vector to the Sun $\hat{x}_\odot$ is defined relative to a spacecraft coordinate system in sketch 2.

Sketch 2. Pointing Angle definitions for locating the Sun relative to a spacecraft.




For this analysis, it is convenient to assume a circular orbit, so that the heading vector $\hat{H}$ is parallel to the velocity vector of the spacecraft. The "pitch" angle $\alpha$ locates the Earth's horizon at the instant of a sunrise or set (it then has a negative value) and the "yaw" angle $\beta$ locates the Sun relative to the direction of spacecraft motion. The three unit vectors $\hat{r}$, $\hat{H}$, and $\hat{N}$ form a Cartesian coordinate system.

With the above discussion and definitions, it is possible to examine a set of sunrise and sunset data for a hypothetical 1-year mission. Figure 1 shows the variation of several important mission parameters as a function of time for 5635 revolutions (approximately 1 year) of a 439 -km, $57^{\circ}$ orbit--some relevant orbital data are listed in table 1. This altitude and inclination is near the limit of the nominal orbit injection capabilities of the shuttle system launched from the Eastern Test Range. The inclination is chosen as high as possible to maximize the potential latitude coverage; the reason for the choice of this particular altitude will become clear when this same orbit is used as one of a two-orbit pair in the dual satellite mission analysis. Figure 1(a) shows the variation in tangent latitude of the measurement point as a function of time from launch, which is arbitrarily chosen as the instant of the Vernal Equinox, 1981. Although the curves look continuous, they are really just discrete points, about 16 per day. The latitude-time cycles are characteristic of these missions. They are driven by the orbit plane precession relative to the Sun. According to table 1, $\dot{\Omega}$ is about -4.3 degrees/day relative to an inertial framework, so the orbit plane precesses about -5.3 degrees/day relative to the Sun. Typically, there are short periods of continuous sunlight on the spacecraft in the summer and winter when the Sun is away from the equator. Note the extension of the measurement latitudes beyond $\pm 57^{\circ}$, as mentioned previously. It is necessary to realize that solar position during the year and the orbit inclination and altitude define an envelope of possible latitudes for measurements, while the time of day of the launch determines the position of the cycles within the envelope. Thus, this nominal case is only a specific example, fixed by choosing a particular launch time (noon). Figure 1(b) shows the pointing angle $\beta$, the "yaw" angle previously discussed, required to locate the Sun during the measurements. It is expected that the requirement will be $\pm 180^\circ$ due to the constantly variable spacecraft-Sun geometry. The values of $\beta$ are near $0^\circ$ or $\pm 180^\circ$ when the Sun is ahead of or behind the spacecraft and near $\pm 90^\circ$ when the Sun is off to the side--often near periods of total sunlight. The symmetry evident in the time history of $\beta$ for sunrises and sets is encouraging from the point of view of rapid acquisition of the Sun during a sunrise measurement, when the value of $\beta$ from the previous sunset can be used to calculate the pointing angle for a sensor prior to the sunrise. Figures 1(c) and (d) show the longitude-latitude distribution of the measurements for sunrise and set. Over a 1-year period, the patterns which make up this fairly dense distribution are not at all clear--much shorter time periods need to be examined to determine how the coverage proceeds with time. Figure 1(e) shows the apparent vertical rate $V_{rel}$ of the Sun relative to the horizon at the instant of sunset or sunrise. To the extent that $V_{rel}$ is constant during the course of a measurement, its value at this time can be used to calculate directly the amount of time available for measurements in the stratosphere: a typical value is about 2 km/sec. This linearization breaks down when the relative velocity approaches zero, and detailed examination of such cases are required to determine the actual measurement strategy. The values of $V_{rel}$ are related to $\beta$, with the largest values occurring near $\beta = 0^\circ$ or $\pm 180^\circ$ and the smallest values near $\beta = \pm 90^\circ$. In the limit, if the spacecraft could fly parallel to the solar terminator, the Sun would appear stationary on the horizon and $V_{rel}$ would be zero.

Figure 2 gives the same data as figure 1, but on an expanded time scale which covers only 30 days. Here, distribution patterns of the coverage are more apparent in the longitude-latitude plots. In figure 3, the longitude-latitude coverage is shown for the first 16 orbits (about 1 day), so that the measurement opportunities can be seen to cover 360° of longitude in roughly 24° steps during a period of time (a day) during which the tangent latitude changes very little. This pattern is typical, but can be significantly altered for the regions where very slow sunrises and sets occur; then the latitude changes more rapidly from one opportunity to the next. The 16 orbits are numbered so the progression with time will be clear. This pattern of longitude-latitude coverage, which will be reproduced in a general way for any similar solar occultation mission, suggests the availability of a certain type of result from data analysis: longitudinally averaged quantities in bands of latitude. Such data, often called zonal averages, are useful for global models of many constituents which exhibit strong latitudinal variability and a much weaker longitudinal structure (ozone is a good example of such a constituent). The patterns also imply that, for such longitudinally averaged data, temporal resolution will be limited to times longer than 1 day; the process of longitudinally averaging the solar occultation data is simultaneously temporal averaging, as the longitude and time are directly related.

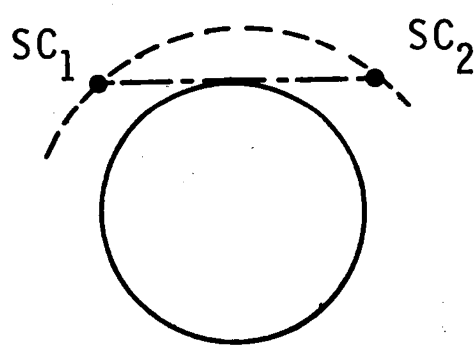
Before leaving the nominal solar occultation mission, there are some data of engineering interest which are presented in figures 4 and 5. Figure 4 shows the fraction of time each orbit spends in the sunlight during a year, and figure 5 is the angle between the unit spacecraft angular momentum vector (a vector normal to the orbit plane) and a unit vector to the Sun. These data are often required for analysis of thermal control systems on proposed space missions.

## DUAL SATELLITE MISSIONS

Analogously to the solar occultation missions, the dual satellite concept seeks to provide an orbiting energy source which rises or sets on the horizon relative to some detector. A laser is the most obvious source of energy, and this may be placed on the second satellite or on the detector satellite, in which case the second satellite serves as a passive reflector of optical energy. It is hoped that the advantage of the dual satellite concept, from the point of view of orbit design, will be that the location of the energy source is more at the discretion of the mission planner. While this is true to a certain extent, it will be seen that other considerations, like a need for repetitive and/or continuous measurement opportunities, impose severe restraints on the concept which force trade-offs between capability and requirements, much as are encountered in the seemingly more restrictive solar occultation concept.

One easily visualized realization of a dual satellite experiment is to place both satellites at the same inclination and in the same orbital plane. The second satellite can be moved ahead of or behind the first until it reaches the horizon. This simple geometry is shown in sketch 3.

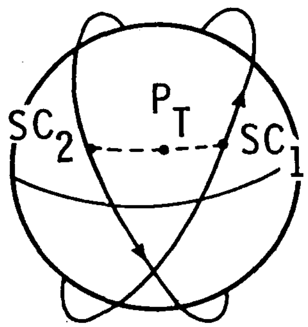
Sketch 3. Geometry for a coplanar dual satellite experiment.



Apparent motion of the second satellite through the atmosphere can be accomplished with small propulsive maneuvers of either satellite, or by placing one of the satellites into an elliptical orbit, preserving the same nodal period and nodal precession rate. The difficulty with this scheme is that rises and sets are very slow (relative to those typically encountered on solar occultation missions, for example), with very poor longitude-latitude resolution as a consequence. The major disadvantage of this scheme for long-term missions is that if the nominal geometry is altered by even a small amount--gradually through cumulative effects of gravitational perturbations or at the outset due to orbit injection errors--there may be a complete mission failure, with no occultations at all. Possible useful applications of this approach to short-term precursor missions will be considered in a later section of the paper.

A much better way of setting up orbit pairs for long-term occultation measurements is shown in sketch 4.

Sketch 4. Nominal geometry for a proposed class of long-term dual satellite missions.



Here, the orbit planes are initially separated by some amount, roughly 150° in the sketch, such that they move relative to each other at orbital speeds, and one appears to rise or set relative to the other at rates comparable to the solar occultation case. In this scheme, the idea is to fix the relative orbit plane orientation and simultaneously to vary the nodal period of one satellite in such a way that the tangent latitudes at which occultations occur continuously change in a predictable and repetitive way. That is, it is desired that:

$$\dot{\Omega}_2 = \dot{\Omega}_1 \qquad (7)$$

$$\tau_{N2} = c\tau_{N1} \qquad (8)$$

where c is a constant yet to be specified. The constant nodal separation between the orbit planes is a value to be determined parametrically; it is through this choice, and the freedom in selecting c, that some flexibility can be brought into the analysis, although there are considerable constraints on the system due to the need to satisfy equations (7) and (8) simultaneously.

The system of equations (7) and (8) are to be solved simultaneously for $a_2$ and $i_2$, given $a_1$ and i, (assuming circular orbits so that $e_1 = e_2 = 0$). Making the appropriate substitutions from equations (1) and (6):

$$\frac{\dot{M}_1 \cos i_2}{a_2^2} = \frac{\dot{M}_1 \cos i_1}{a_1^2} \qquad (9)$$

$$\frac{2\pi}{\tau_{N2}} = \dot{M}_2[1 + \frac{3}{2} J_2 \frac{r_\oplus^2}{a_2^2} (2 - 2.5 \sin^2 i_2)] = \frac{\dot{M}_1}{c}[1 + \frac{3}{2} J_2 \frac{r_\oplus^2}{a_1^2} (2 - 2.5 \sin^2 i_1)] = \frac{2\pi}{c\tau_{N1}} \qquad (10)$$

Suppose that $\tau_{N1}$ = 5600 sec and $i_1 = 57^\circ$. Then, from equations (6), (5), and (2), $a_1$ = 6817.028 km ($h_1$ = 438.883 km). Now suppose c = 11/10 ($\tau_{N2}$ = 6160 sec) so that the satellites will return to their initial orientations after 11 revolutions of satellite 1. Now, equations (9) and (10) can be solved to yield $i_2 = 47.051^\circ$ and $a_2$ = 7268.214 km ($h_2$ = 890.068 km) so that $\dot{\Omega}_2 = \dot{\Omega}_1$ = -4.298 deg/day. These two orbits form a pair whose orbit planes maintain a constant relationship to each other and for which the latitude tangent point coverage pattern, whatever it is, will repeat indefinitely with a cycle time of 61,600 sec. These patterns will be examined in a subsequent section, but first the parametric aspects of establishing these types of orbit pairs need to be investigated.

For a particular choice of the first orbit of the pair, there are an infinite number of second orbits, corresponding to the choice of c. If c is restricted to the rational numbers (it is only convenient, not necessary, to do so), the repeat cycle in time is easily established in terms of integral multiples of one orbit or the other. The variation of $i_2$ and $h_2$ (in place of $a_2$) with c as a parameter is shown in figure 6. The "+" marks correspond to $i_1$ and $h_1$. The shaded area shows the presumed nominal operating range of the shuttle system without additional propulsive capability. It can be seen that $i_1 = 57^\circ$ and $h_1$ = 438.883 km are, in fact, just within these nominal limits. It is also evident that the altitude and inclination space required to exercise a wide range of parametric choices for these orbit pairs is much larger than that available to the early shuttle system, indicating the general need for Western Test Range launch capability and additional propulsion to take advantage of this type of dual satellite mission.

Also shown in figure 6 are two other choices for the first orbit along with the corresponding second orbit parameters. In one case ($i_1 = 57^\circ$, $\tau_{N1} = 6000$ sec, $h_1 = 759.646$ km) the idea is to allow higher inclination second orbits to achieve better latitude coverage. The altitude of the second orbit goes down as its inclination goes up, so the limit is imposed by the lowest practical altitude for space operations, which is about 250 km. The remaining case attempts to find an orbit pair, both of which are within the nominal shuttle capability. If $i_1 = 57^\circ$, and $\tau_{N1} = 5370$ sec ($h_1 = 250.99$ km), then the smallest value of c which will fit in the shuttle envelope is c = 23/22 ($i_2 = 52.80^\circ$, $h_2 = 452.08$ km). For completeness, table 2 lists some second orbit parameters for the three first orbit choices discussed above, over a range of c values.

As an interesting sidelight, two orbit inclinations favored by the Soviet Union in their space program--around 52° and 65° (ref. 3)--coincide neatly with two desirable second orbits in the types of pairs studied here, making this dual satellite concept an obvious choice for joint space missions having potentially broad global implications for atmospheric monitoring.

For examining the types of coverage patterns to be expected for these dual satellite missions, the nominal choice of orbits is not a critical factor. A pair has been chosen for which $\tau_{N2} = (16/15)\, \tau_{N1}$. Orbit parameters are listed in table 3. One of these is within the nominal shuttle performance envelope, as previously discussed, while the other, at lower inclination, requires additional propulsion to reach the proper altitude. The periods are adjusted so that the latitude repeat cycle is about 1 day. Note that the first orbit is identical to the solar occultation nominal mission so that coverage capability can be equitably compared between the two missions. It is worth noting also that picking the first nodal period to be a "round" number is just an arbitrary choice for convenience. Exact specification of all orbit parameters is necessary only to guarantee the desired long-term internal consistency in the orbit propagation program. The sensitivity of the results to the precise values of the orbit parameters will be discussed later in the analysis.

Before showing some data for this pair of orbits, it is necessary to establish what nodal separation to use. Figure 7 shows the number of measurement opportunities per cycle (16 nodal revolutions of the first orbit) as a function of nodal separation. The maximum of 30 (15 rise-set pairs) occurs at around $\Delta\Omega = 160^\circ - 180^\circ$; $160^\circ$ will be used as the nominal.

Figure 8 shows some basic parameters of interest for the nominal orbit pair over a 30-day period. These data correspond to figure 2 in the solar occultation analysis. Because of the seasonal independence of the dual satellite measurements, it is not necessary to generate a year's worth of data to get a good idea of mission potential. In fact, with the orbital constraints of the nominal mission, only the measurement longitude does not repeat once every 16 nodal revolutions of the first orbit. Figure 8(a) shows the latitude-time coverage for 30 days; (b) shows the pointing angle $\beta$ as a function of time; (c) shows the tangent longitude-latitude coverage with rises and sets combined into one plot; (d) shows the apparent vertical rate of the Sun $V_{rel}$ relative to the horizon. The range of values encountered for each of these quantities are not much different from those encountered during solar occultations, but the patterns are evidently quite different. To examine the differences in detail, the graphic output from 16 nodal revolutions is shown in figure 9, with an expanded scale on the time axis. Figure 9(c) corresponds to figure 3 of the solar occultation analysis. However, the numbers correspond not to orbits, but to measurement opportunities, in rise-set pairs. Note that occultation opportunities are available during about half the 1-day cycle time. For generating figures 8 and 9, both satellites are started on the Equator. This is a restriction which could be removed to allow additional parametric verification, but it is relatively insignificant for the present purpose. The basic result of changing the starting positions is to shift the patterns of figure 9 horizontally along the time or longitude axis. In this way, it is possible to exercise some control over when during the day the measurement opportunities occur.

Unlike the solar occultation mode, where the coverage, pointing angles, and vertical rates undergo cycles driven by the seasonal motion of the Sun and the precession of the orbit plane relative to the Sun, these same quantities cycle within the space of a single day on the nominal dual satellite mission. An advantage for this orbit pair, and for others which exhibit similar repetitive coverage patterns, is that the measurements are made regularly at a series of constant latitudes--the number and location of which are dependent on the value of c. Departures from the nominal orbit can occur either in the actual value of c obtained or in the placement of the orbital planes. In the first case, the result is mostly longitude displacements and variable latitude coverage of the measurement tangent points, which may not follow an obvious short-term cyclic pattern. The remedy is to raise or lower the orbits, thereby adjusting the periods to the proper values. The second case can be thought of in terms of time equivalents with 15° of nodal separation corresponding to a 1-hour difference in launch time. To avoid the depletion of coverage opportunities depicted in figure 7, the nodal separation needs to be initialized and maintained in the general vicinity of 180°--12 hours. Fortunately, the separation is not critical around the required values so that a launch window of several hours is available. Once the orbit pair is established, regardless of whether the nominal periods are obtained, the first priority is to maintain the nodal separation: this determines the long-term behavior of the mission. Then, the secondary goal is to maintain the periods of each orbit to achieve the short-term repeatability of latitude coverage which is a desirable characteristic of this mission concept.

Some data of potential engineering interest for the dual satellite mission are given in figure 10. Here, the pitch and yaw rates (the rates for the $\alpha$ and $\beta$ angles as previously defined) are shown for 30 days of the nominal mission. The pitch rate range is about $\pm$ 0.05 deg/sec, while the yaw rate range is about $\pm$ 0.12 deg/sec. It is clear from this figure, and figure 8(b), that pointing and tracking requirements for the dual satellite concept are more complex than those for the solar occultation mode. Hardware concepts for achieving the necessary flexibility have not yet been investigated.

To give some additional insight into the performance of dual satellite missions, the longitude, latitude, and time data have been "boxed" in a 10-degree by 10-degree spatial grid. Rather than dealing with local clock time, it is of more interest to relate the measurement point directly to the location of the Sun. This is done in a relative hour angle system, wherein the angle between the tangent point meridian and the subsolar meridian is given a time equivalent, with 15 degrees equal to 1 hour. In this system, 12 hours can be defined as high noon--where the two meridians coincide. In this time system, the values do not contain any information about the season; some other measure of solar position, like zenith angle, is needed to specify the seasonal effects of apparent solar motion relative to the Equator. Table 4 summarizes longitude-latitude data for the 30-day nominal mission. These are just the data of figure 8(c) in tabular form. Tables 5, 6, and 7 summarize relative hour angles for the same 30-day period. First, table 5 shows the hour angle data summed over all longitudes, for 10-degree latitude bands. Then, tables 6 and 7 give these data in 10-degree longitude segments for the latitude bands between $0^{\circ}$ - $10^{\circ}$ and $40^{\circ}$ - $50^{\circ}$. The observed time patterns are typical of the dual satellite missions and may be contrasted with the solar occultation case, for which the relative hour angle is always exactly 6 a.m. or 6 p.m. at the Equator. Thus, in table 6, all the measurements for solar occultation would be in the 6-7 and 18-19 boxes.

Tables 5, 6, and 7 indicate the possibilities for obtaining zonal averages (that is, data within specified ranges of latitudes, averaged over longitude and time). The data are reasonably evenly spaced in longitude and they include some diurnal information. The length of time required to obtain diurnal data depends on the value of c--that is, on how many latitudes are available for measurements during a nominal mission cycle. It is not surprising to find that getting more diurnal information more quickly requires giving up some of the latitude bands. For the present nominal mission, 24 hours' worth of diurnal information is obtained in about 30 days near the Equator. The adequacy of this performance and the extent to which longitude and time information can be separated within latitude bands depends on what is being measured and what knowledge already exists or is being sought about its distribution. The dual satellite concept has at least the potential for separating these effects in a way which is not possible in the solar occultation mode.

## AN EXAMPLE OF OCCULTATION MISSION DATA ANALYSIS

As an example of how occultation data might be used for global modeling of atmospheric constituents, the nominal 1-year solar occultation mission has been used to generate a simulated set of measurements. The time, longitude, and latitude of each sunrise and sunset (about 10,500 measurement opportunities in all) have been input to a distribution model which produces a single dimensionless number, Q, as output at each condition--it could be related to a total vertical burden, for example. The details of the model and the physical interpretation of the output are not too important: however, the variability with latitude is typical of that observed in total ozone data*. The goal of this exercise is just to compare a simulated data set against the "real world" which in this case is the output of the model as would be revealed by knowledge of its inner workings or by a perfect sampling scheme. The apparent suitability of occultation measurements for producing zonal averages has been mentioned previously. Consequently, the strategy for analyzing the simulated data has been to divide all the measurements into 5-degree latitude bands and then to

*Data for such total vertical burdens can be obtained from: The Scientific Panel on the Natural Stratosphere: The Natural Stratosphere of 1974. Dept. of Transportation, Climatic Impact Assessment Program, CIAP Monograph 1, 1974.

separate and average them according to temporal groupings. A detailed discussion of that process is beyond the scope of this paper. One possible result of the data analysis is shown in figure 11. Here, the yearly zonal averages of Q, $\bar{Q}$, are plotted as a function of latitude. Each point is a weighted mean and it has associated with it a standard deviation which is shown by the bars. The solid line is obtained directly from the model and represents the "real world" calculations of $\bar{Q}$ . Extensive statistical analysis of such data sets is a complex endeavor which goes beyond the scope of this paper. For example, the relationship between the observed means and actual means depends in an uncertain way on the amount and distribution of data. The differentiation, in the standard deviation, between a truly random contribution and unperceived variability is difficult. Application of statistical tests to such data is often hampered by variable and sometimes small samples which are obviously not properly distributed. This prevents the straightforward assignment of confidence limits on means (in the statistical sense). Nonetheless, it is qualitatively clear that yearly zonal information can be obtained over a large portion of the globe, with an accuracy which may be adequate for many purposes. Studies with this type of data have demonstrated that yearly and seasonal averages can be formed in several different ways, and longitude-latitude-time models can be extracted with spatial resolutions of about 5 degrees in latitude (somewhat coarser in longitude) and temporal resolutions of no better than several days.

## STRATEGY FOR PRECURSOR MISSIONS

The basic concept of occultation measurements has been formulated around the need for long-term--perhaps permanent--global monitoring of atmospheric constituents. Toward this end, the types of coverage provided by solar and dual satellite occultation missions such as proposed in the previous sections can provide major inputs of data not obtainable in other ways. However, in the process of justifying this worthwhile long-range goal, shorter missions are useful for investigating and demonstrating the feasibility of many aspects of measurement techniques, hardware, and strategy. Such precursor missions have the added advantage of being compatible with early shuttle flights lasting a week or so.

## Solar Occultation Precursor Missions

For the solar occultation technique, an obvious and useful precursor mission is to extract a "piece" of the nominal mission, of any length, and simply make measurements in the nominal way. As mentioned previously, the orbit parameters and season determine the envelope within which measurements are available, while the measurements actually obtained depend on the local time of the orbit injection-- more directly, on the position of the Sun relative to the orbit plane. It is not at all certain that such an experiment could be the controlling factor in selecting a launch time for shuttle flights, so the available conditions could range from measurements at high, nearly constant latitude to no measurements at all, in the worst case. Near periods of total sunlight--before or after--there exist opportunities for covering a wider range of latitudes in just a few days. Achieving these conditions means launching in the summer or winter, and at the right time of day. In exchange for this, the measurement times become long (as $V_{rel}$ approaches zero), and the spatial resolution of, for example, a vertical profile suffers. However, the longer times may allow less automated systems to be used at a relaxed man-in-the-loop pace, possibly improving signal-to-noise ratio (with longer signal integration times) enough to allow measurements to be made which could not be included on the nominal mission.

## Dual Satellite Precursor Missions

Technological aspects of the laser-dual satellite concept can be explored by returning to the coplanar geometry which was considered inadequate for the long-term mission. In this way, the separate placement in different orbits of two satellite systems can be avoided. Any of the shuttle launches scheduled for the 1980's could be utilized to carry a receiver satellite to orbit along with a laser transmitter, which will remain on the shuttle. The shuttle and receiver satellite will remain coplanar, but the orbital altitude of the shuttle will be maneuvered to separate and phase the two systems such that the line of sight will pass through the atmosphere. (The maneuvering capability could, of course, be onboard the receiver satellite if that were desired.) These maneuvers would not allow quick vertical profiles to be made, as in the nominal mission. Rather, they would tend to be continuous measurements at slowly varying altitude, lasting on the order of 1 or more days, depending on how the phasing maneuvers are accomplished. Thus, this proposed precursor mission is substantially different from its nominal counterpart. Its purpose is to provide flight testing for the potentially complex hardware involved. On the scientific level, the measurements could be directed toward those trace species which require very long signal integration times, or those whose spatial distributions are not expected to show strong longitude-latitude or temporal variability.

The phasing maneuvers for a hypothetical short shuttle flight are shown conceptually in figure 12. A nominal 400-km altitude is assumed. After system checkout on the shuttle, the free-flying receiver satellite is removed from the payload bay. The shuttle then transfers and circularizes to a new orbit at 428 km to obtain a longer orbital period that will produce a gradually increasing separation between shuttle and receiver. A total velocity increment ($\Delta v$) of 16 m/sec is required for these maneuvers. During the second day of the mission, the angular separation between shuttle and receiver increases to 34.2 degrees. At the beginning of the third day, the shuttle transfers back nearly to its original orbit, to 402 km ($\Delta v$ = 15 m/sec). Now the shuttle and receiver are viewing each other at a nominal tangent point altitude of 100 km. Over the next 2 days, the slight differences in orbital period cause the separation angle to increase so the tangent altitude decreases at a rate of about 3 km per orbit. During this 2-day period, shuttle and receiver are in constant line-of-sight contact so that the acquisition and pointing problems evident in the nominal mission are greatly alleviated. Since the Earth is not perfectly round and because of the difficulties in exact determination of the tangent altitude just from orbital data, the actual tangent altitude should be determined more directly with the mission systems. The geometric height is not really necessary; a pressure height may be determined from temperature measurements with a $CO_2$ laser, a perfectly adequate procedure which will probably suffice and is required for data inversion, even on the nominal mission. During the 2-day measurement period, the separation between shuttle and receiver increases from about 4000 to 4600 km. The impact of this separation distance on laser power requirements is yet to be determined; it is a strong function of the available optics. However, it appears that current technology for some of the most useful signal sources, tunable diode lasers, precludes passive reflection of laser signals from the shuttle, to a reflector, and back to a receiver on the shuttle*. So, the receiver satellites probably will have to have an active onboard receiving system.

The rate at which the tangent altitude changes is, of course, dependent on the difference between the shuttle and receiver altitudes (equivalently, their periods) during the measurement phase of the mission. There are two measurements per orbit at each available latitude. Thus, for the 2-km difference shown in figure 12, there are about 60 points in 2 days at each latitude for establishing a vertical profile--each measurement is separated from the next by about 12 hours of local clock time at the measurement point on (or over) the Earth's surface. The ability to generate such profiles in a meaningful sense depends generally on measuring some quantity which has a known or no diurnal or longitudinal variability. If the receiver and shuttle altitudes are 400 and 401 km, respectively, then the measurements could extend over 4 days instead of 2 and there would be 120 points at each latitude.

At the end of the 2-day measurement period, the shuttle and receiver can be rejoined--roughly speaking, by reversing the previous maneuvers. The entire mission requires less than a week and nominal propulsive maneuvers totaling less than 70 m/sec. The orbit changes are so small, in fact, that it may well be difficult to adhere rigidly to a prescribed nominal plan. However, it is clear that such phasing maneuvers can be performed, and that something similar to the conceptual mission can be achieved within the allotted time.

*Private communication, J. M. Hoell, Jr., LaRC, July 1977.

## DISCUSSION OF RESULTS

The previous sections have demonstrated some of the possibilities for representative occultation missions. A common feature of both approaches--solar and dual satellite occultation--is the availability of measurement sets for long-duration missions which allow averages to be taken within bands of constant or restricted latitude (zonal averages). This results from the relatively slow motion of the Sun and of orbit planes in inertial space compared to the Earth's rotation. The satellite motion need not (and in the dual satellite case, cannot) be coupled to the Earth's rotation rate, because this is an additional constraint on the orbit parameters which has no bearing on the occultation measurement. Thus, the distribution of points in longitude tend to be fairly uniformly spaced out around the Earth, without repetition, as could be the case for orbits designed specifically for repetitive groundtrack coverage.

The range of latitude coverage is determined mostly by orbit inclination, although in neither case are the measurement latitudes restricted to the maximum latitude of the groundtrack. This is due to the secondary effect of orbit altitude which can, for example, allow the Sun to be viewed as it rises or sets over the poles by a satellite at less than $90^{\circ}$ inclination. For moderate altitudes, an inclination of about $70^{\circ}$ is sufficient to allow some polar coverage in the summer and winter. In the dual satellite case, there is no conceptual difficulty with using orbit pairs at high inclinations. In both cases, the restraints on inclination have been imposed in this paper only by a consideration of what orbital space (altitude-inclination) will first be available from early space shuttle launches.

The time coverage of these two occultation techniques is fundamentally different. In solar occultation, the measurement always takes place at local (ground) dawn or dusk, regardless of the clock time or relative solar time (as previously defined). Thus, diurnal cycles are not accessible with this technique. Quantities which undergo diurnal variation often change rapidly just at dawn or dusk, so that measuring them at this particular time has a good chance of adding additional uncertainty to the data analysis. Even if the diurnal cycle is not in phase with the dawn-dusk cycle, solar occultation measurements are still not very useful for establishing what the actual behavior is. On the other hand, the dual satellite measurement can and will be made at all local times. The temporal coverage patterns are not random, though, and it may take anywhere from several days to several months to fill in 24 hours of diurnal data for a measured quantity. An additional difficulty here is that time is strongly coupled to longitude in a way which is constantly changing throughout the mission. In figure 9(c), for example, the alternation between longitude points on opposite sides of the globe is easily seen as being equivalent to a gradually drifting day-night alternation. This makes separation of longitude and time effects difficult in the absence of a prior understanding of the behavior of the quantity of interest. It is especially the coupling between time and longitude which makes statistical interpretation of occultation measurements difficult. Within a latitude band, it prevents the measurements from being independent, or uniformly distributed over the sample space. In the example given for yearly zonal averages, the problem of interpretation at the extreme latitudes covered is not so much a lack of measurements as it is a clear seasonal bias in those measurements which are available.

The solar occultation mode provides on the order of $10^4$ measurement opportunities per year, depending on orbit inclination, and the dual satellite mode can yield about the same number, depending on the orbit plane geometry and the difference in period between the two orbits. The solar occultation measurements are made regularly at a rate of two per orbit, except for the short periods of total sunlight which can occur during the summer and winter. The dual satellite measurements are made at a rate of four, two, or zero per orbit, with periods of measurement alternating with no measurements within a day's time. In both cases, the precise timing and location of measurements is a function of orbit parameters and launch timing. Thus, the nominal cases only serve as guides for assessing the potential of these measurement techniques. They are not intended to present specific missions to be flown or favored over others in their particulars.

There are several systems problems associated with occultation measurements. The most obvious concern acquisition and pointing. With the Sun as a source, the change in pointing angle with time is slow and predictable, and the observed symmetry in pointing between sunrise and sunset allows the conditions at sunset to be used to predict conditions for the next sunrise (see fig. 1(b)). Clearly, it is critical to be able to predict as closely as possible the location of the source just before it begins to rise over the horizon so that valuable measurement time will not be wasted in a scanning search. An acceptable system must have the capability for remote adjustment of its programmed pointing history as well as an active lock-on system. The former is necessary to compensate for launch timing variations which could drastically alter the entry point into what should be a reasonably predictable pointing cycle. The latter is needed for fine pointing in nominal operation and perhaps for a search mode of operation in off-nominal situations. For the dual satellite mission, the acquisition problem is much more severe. Even in the nominal case (see fig. 8(b)) the pointing system must be capable of accommodating extreme changes in direction from one measurement opportunity to the next, which may be only minutes apart. In principle, the pointing history is deterministic and could be preprogrammed. However, the chances of nominal operation for long periods of time are remote, as the conditions are so sensitive to orbit parameters and timing. It appears that a wide-angle search system is needed (wide relative to the field-of-view for processing the measurement signals) with constant active updating of the predicted future pointing history. Taking 2 km/sec as a typical apparent vertical rate of the source rising on the horizon, it takes only 50 sec to pass through the first 100 km of atmosphere, so acquisition and measurements all have to be done within this time span. Failure to accommodate these requirements carries the penalty of losing half of all the measurement opportunities. The solution may result in a source containing three separate transmitting systems--one for acquisition and pointing (a "homing" signal), one for geometric or pressure height determination, and one for the specialized task of taking the measurements. Other parts of the pointing problem involve control of the sensor pitch and yaw rates, as in figure 10, and avoiding direct or prolonged exposure of sensors to the Sun, a situation briefly outlined in figures 4 and 5. Finally, there is nothing in these orbit design data which precludes the possibility of combining solar and dual satellite measurements on a single mission, although this is a substantial complication of the planning logistics.

It is important to consider the data output from these missions as an entity, with distributional aspects that favor particular interpretations on the global scale. For global models of, for example, total vertical burden of atmospheric constituents, the three dimensions of longitude, latitude, and time form the relevant coordinate system, and a readily apparent way to utilize occultation data is to form latitude bands, as in the example of figure 11. A general characteristic of satellite data, and one which is evident in the cases presented here, is lack of control over the experiment design in a statistical sense. Thus, even within an adequately defined latitude band, it is not possible to structure the remaining data--longitude and time--in the desired way for straightforward statistical analysis. This is due to the sequential nature of satellite measurements and the relentless, if often obscure, relationship between time and longitude which prohibits "turning back" to fill in missing data. Nonetheless, considerable distributional information can be extracted from occultation measurements and it is these statistical aspects of the missions which pose the greatest challenge for further investigation.

## SUMMARY

Two types of satellite-based occultation missions have been considered for measuring atmospheric constituents. Nominal cases for each type have been presented to demonstrate representative solutions to orbit design problems. In the first case, a 1-year solar occultation mission is simulated. Here, a satellite views the Sun as it rises or sets on the horizon. The potential for space and time coverage has been illustrated;

latitudes between about $\pm$ 75° are covered on up to 22 different occasions during a year. Some engineering parameters are shown which define the need for considerable sophistication and flexibility in the source acquisition and pointing system. The main limitation of the solar occultation technique is the restriction of measurements to local dawn and dusk, a situation which can be relieved by the use of dual satellites at the expense of more costly and complex systems. This technique uses a laser on one satellite as a source to replace the Sun and a receiver on a second satellite. It has been shown how to identify pairs of satellite orbits whose orbit planes maintain a constant geometrical relationship in inertial space, with differing periods to provide cyclic opportunities for occultation measurements at a number of different latitudes. A nominal case has been illustrated with graphic output which can be compared on an equivalent basis to the solar occultation case. This orbit pair cycles through about $\pm$ 50° of latitude coverage in less than a day.

It may take a month or two for two satellites to obtain complete diurnal data over the available spatial grid, and separation of time and space effects on the observed variability in the data is a potentially difficult problem. Occultation measurements tend to provide good capability for computing zonal averages--measurements averaged over longitude and time in bands of constant or restricted latitude. An example of such zonal averages has been given for the simulated 1-year solar occultation mission using a single-parameter output model whose variability is similar to that observed for the total vertical burden of ozone.

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2. Anonymous: Space Flight Handbooks, Volume 1: Orbital Flight Handbook, Part 1-Basic Techniques and Data. NASA SP-33, Washington, DC, 1963.

3. Anonymous: Soviet Space Programs, 1966-70. Staff Report prepared for the use of the Committee on Aeronautical and Space Sciences, United States Senate, by the Science Policy Research Division and Foreign Affairs Division of the Congressional Research Service and the European Law Division of the Law Library, Library of Congress. Senate Document No. 92-51, December 9, 1971.

Table 1. Orbit Parameters for the Nominal Solar Occultation Mission

$a = 6817.028$ km ($h = 438.883$ km)

$e = 0$

$i = 57^\circ$

$\tau_N = 5600$ sec

$\dot{\Omega} = -4.2985$ deg/day

$\dot{\omega} = 1.9067$ deg/day

$\dot{M} = 5552.379$ deg/day

Table 2. Dual Satellite Orbit Pairs for Which $\dot{\Omega}_2 = \dot{\Omega}_1$, and for Which the First Orbit has $i = 57^\circ$, at Three Different Circular Altitudes.

| c | $\tau_N$ | a, km | (h), km | i, deg | $\dot{\Omega}$, deg/day | |
|---|---|---|---|---|---|---|
| | 5370.00 | 6629.137 | ( 250.992) | 57.000 | -4.740 | 1st orbit |
| 61/60 | 5459.50 | 6703.190 | ( 325.045) | 55.514 | | |
| 31/30 | 5549.00 | 6776.875 | ( 398.730) | 53.967 | | |
| 21/20 | 5638.50 | 6850.193 | ( 472.048) | 52.353 | | |
| 16/15 | 5728.00 | 6923.156 | ( 545.011) | 50.666 | 2nd orbits | |
| 11/10 | 5907.00 | 7068.061 | ( 689.916) | 47.046 | | |
| 9/ 8 | 6041.25 | 7175.860 | ( 797.715) | 44.076 | | |
| 7/ 6 | 6265.00 | 7353.983 | ( 975.838) | 38.496 | | |
| 6/ 5 | 6444.00 | 7495.109 | (1116.964) | 33.240 | | |
| 5/ 4 | 6712.50 | 7704.747 | (1326.602) | 22.935 | | |
| | 5600.00 | 6817.028 | ( 438.883) | 57.000 | -4.299 | 1st orbit |
| 19/20 | 5320.00 | 6586.231 | ( 208.086) | 61.127 | | |
| 29/30 | 5413.33 | 6663.577 | ( 285.432) | 59.803 | | |
| 59/60 | 5506.67 | 6740.504 | ( 362.359) | 58.428 | | |
| 61/60 | 5693.33 | 6893.146 | ( 515.001) | 55.515 | 2nd orbits | |
| 31/30 | 5786.67 | 6968.884 | ( 590.739) | 53.968 | | |
| 21/20 | 5880.00 | 7044.243 | ( 666.098) | 52.355 | | |
| 16/15 | 5973.33 | 7119.236 | ( 741.091) | 50.669 | | |
| 11/10 | 6160.00 | 7268.165 | ( 890.020) | 47.051 | | |
| 9/ 8 | 6300.00 | 7378.953 | (1000.808) | 44.083 | | |
| 7/ 6 | 6533.33 | 7562.004 | (1183.859) | 38.507 | | |
| 6/ 5 | 6720.00 | 7707.026 | (1328.881) | 33.257 | | |
| 5/ 4 | 7000.00 | 7922.429 | (1544.284) | 22.970 | | |
| | 6000.00 | 7137.790 | ( 759.645) | 57.000 | -3.660 | 1st orbit |
| 9/10 | 5400.00 | 6650.706 | ( 272.561) | 64.824 | | |
| 14/15 | 5600.00 | 6814.883 | ( 436.738) | 62.402 | | |
| 19/20 | 5700.00 | 6896.285 | ( 518.140) | 61.126 | | |
| 29/30 | 5800.00 | 6977.222 | ( 599.077) | 59.801 | | |
| 59/60 | 5900.00 | 7057.719 | ( 679.574) | 58.427 | 2nd orbits | |
| 61/60 | 6100.00 | 7217.437 | ( 839.292) | 55.516 | | |
| 31/30 | 6200.00 | 7296.681 | ( 918.536) | 53.970 | | |
| 21/20 | 6300.00 | 7375.528 | ( 997.383) | 52.358 | | |
| 16/15 | 6400.00 | 7453.987 | (1075.842) | 50.673 | | |
| 11/10 | 6600.00 | 7609.792 | (1231.647) | 47.058 | | |
| 9/ 8 | 6750.00 | 7725.688 | (1347.543) | 44.093 | | |
| 7/ 6 | 7000.00 | 7917.158 | (1539.013) | 38.525 | | |
| 6/ 5 | 7200.00 | 8068.836 | (1690.691) | 33.283 | | |
| 5/ 4 | 7500.00 | 8294.093 | (1915.948) | 23.022 | | |

Table 3. Orbit Parameters for the Nominal Dual Satellite Mission

| | |
|---|---|
| $a_1 = 6817.028$ km ($h_1 = 438.883$ km) | $a_2 = 7119.254$ km ($h_2 = 741.109$ km) |
| $e_1 = 0$ | $e_2 = 0$ |
| $i_1 = 57^\circ$ | $i_2 = 50^\circ.669$ |
| $\tau_{N1} = 5600$ sec | $\tau_{N2} = 5973.33 = 16/15\ \tau_{N1}$ |
| $\dot{\Omega}_1 = -4.2985$ deg/day | $\dot{\Omega}_2 = -4.2985$ deg/day |
| $\dot{\omega}_1 = 1.9067$ deg/day | $\dot{\omega}_2 = 3.4199$ deg/day |
| $\dot{M}_1 = 5552.379$ deg/day | $\dot{M}_2 = 5203.696$ deg/day |

Table 4. Distribution of Measurement Opportunities Over Longitude and Latitude for the Nominal Dual Satellite Mission, for 30 Days.

Longitude, deg

| Latitude, deg | | | | 30 | | | 60 | | | 90 | | | 120 | | | 150 | | | 180 | | | 210 | | | 240 | | | 270 | | | 300 | | | 330 | | | 360 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 50 | 0 | 4 | 1 | 2 | 0 | 2 | 0 | 2 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 3 | 0 | 3 | 2 | 1 | 2 | 1 | 3 | 0 | 3 | 0 | 4 | 0 | 4 | 0 | 4 |
| 30 | 40 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 2 | 0 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 3 | 1 | 2 | 1 | 2 | 0 | 2 | 0 | 2 | 0 |
| 20 | 30 | 1 | 4 | 1 | 3 | 2 | 2 | 1 | 2 | 3 | 0 | 3 | 0 | 3 | 0 | 4 | 0 | 4 | 0 | 4 | 1 | 4 | 1 | 4 | 4 | 2 | 4 | 2 | 6 | 0 | 6 | 0 | 6 | 0 | 5 | 0 | 5 |
| 10 | 20 | 5 | 1 | 6 | 0 | 6 | 1 | 4 | 1 | 4 | 1 | 3 | 2 | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 5 | 1 | 5 | 1 | 7 | 0 | 7 | 2 | 6 | 2 | 6 | 4 | 3 | 4 | 3 | 6 | 1 |
| 0 | 10 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 2 | 3 | 4 | 4 | 1 | 4 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 2 | 4 | 3 | 5 | 4 | 3 | 4 | 3 | 5 | 2 | 5 | 2 | 4 | 2 |
| -10 | 0 | 5 | 2 | 6 | 3 | 4 | 4 | 3 | 6 | 2 | 6 | 2 | 6 | 2 | 7 | 3 | 6 | 2 | 6 | 3 | 6 | 3 | 5 | 4 | 4 | 6 | 2 | 5 | 3 | 6 | 1 | 6 | 1 | 6 | 1 | 6 | 2 |
| -20 | -10 | 5 | 1 | 5 | 1 | 5 | 2 | 5 | 3 | 5 | 5 | 3 | 4 | 3 | 6 | 2 | 5 | 2 | 5 | 2 | 4 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 3 | 2 | 3 | 2 | 5 | 1 | 4 | 2 |
| -30 | -20 | 1 | 3 | 1 | 3 | 3 | 1 | 3 | 1 | 4 | 0 | 4 | 0 | 4 | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 2 | 1 | 1 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 3 | 0 | 3 | 0 | 3 |
| -40 | -30 | 2 | 3 | 2 | 4 | 2 | 5 | 3 | 3 | 3 | 3 | 4 | 3 | 4 | 2 | 4 | 3 | 3 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 3 | 1 | 2 | 2 | 2 |
| -50 | -40 | 2 | 0 | 2 | 0 | 4 | 0 | 4 | 1 | 3 | 2 | 2 | 2 | 2 | 3 | 1 | 3 | 1 | 3 | 1 | 4 | 0 | 4 | 0 | 2 | 0 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 0 |

Number of measurement opportunities

Table 5. Measurement Opportunities in 10-degree Latitude Bands as a Function of Relative Solar Time (see text) For The Nominal Dual Satellite Mission, for 30 Days.

| Relative Solar Time, Hours | Latitude band, deg 40, 50 | 30, 40 | 20, 30 | 10, 20 | 0, 10 | -10, 0 | -20, -10 | -30, -20 | -40, -30 | -50, -40 |
|---|---|---|---|---|---|---|---|---|---|---|
| 23 24 | 3 | | 3 | 3 | 3 | 6 | 4 | 1 | 1 | |
| 22 23 | 5 | 1 | 3 | 2 | 4 | 6 | 4 | | | |
| 21 22 | 6 | 3 | 6 | 6 | 4 | 8 | 6 | | | |
| 20 21 | 5 | 3 | 6 | 6 | 6 | 9 | 6 | | | |
| 19 20 | 5 | 2 | 5 | 6 | 6 | 9 | 6 | | | |
| 18 19 | 6 | 3 | 5 | 5 | 6 | 7 | 6 | | | |
| 17 18 | 6 | 3 | 6 | 5 | 4 | 8 | 4 | | | |
| 16 17 | 6 | 3 | 6 | 6 | 6 | 9 | 6 | | | |
| 15 16 | 4 | 3 | 5 | 6 | 6 | 9 | 6 | | | |
| 14 15 | 2 | 6 | 6 | 4 | 5 | 8 | 6 | | | |
| 13 14 | 3 | 4 | 2 | 3 | 3 | 2 | 3 | | | |
| 12 13 | 2 | 3 | 3 | 4 | 3 | 5 | 4 | 2 | 1 | |
| 11 12 | | | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| 10 11 | | | 3 | 5 | 5 | 4 | 3 | 2 | 5 | 5 |
| 9 10 | | | 2 | 6 | 6 | 5 | 5 | 6 | 7 | 5 |
| 8 9 | | | 3 | 6 | 5 | 5 | 6 | 6 | 9 | 6 |
| 7 8 | | | 3 | 5 | 5 | 6 | 6 | 6 | 9 | 6 |
| 6 7 | | | 3 | 5 | 6 | 6 | 6 | 4 | 9 | 6 |
| 5 6 | | | 2 | 6 | 6 | 5 | 4 | 6 | 6 | 4 |
| 4 5 | | | 3 | 6 | 5 | 6 | 6 | 6 | 9 | 6 |
| 3 4 | | | 3 | 6 | 5 | 5 | 6 | 6 | 10 | 6 |
| 2 3 | | | 3 | 5 | 6 | 5 | 5 | 4 | 9 | 6 |
| 1 2 | | | 2 | 3 | 3 | 3 | 2 | 3 | 5 | 4 |
| 0 1 | | | 1 | 3 | 4 | 6 | 3 | 3 | 4 | 1 |

Number of measurement opportunities

Table 6. Measurement Opportunities in the Latitude Band from 0 to 10 degrees as a Function of Relative Solar Time (see text) and Longitude for the Nominal Dual Satellite Mission, for 30 Days.

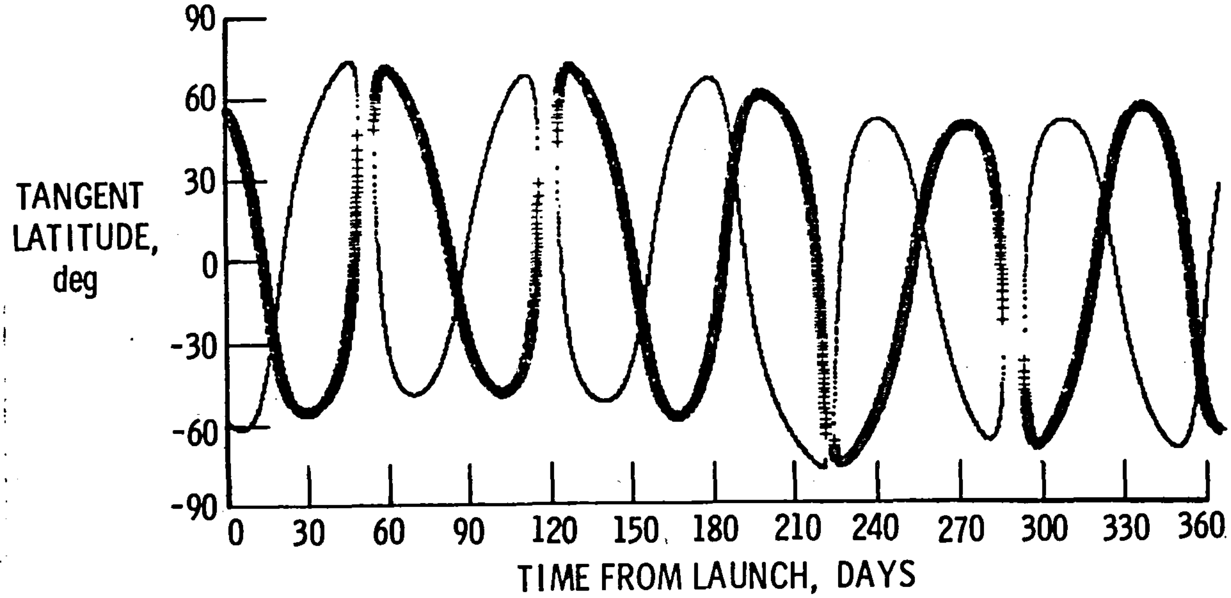
| Relative Solar Time, Hours | | Longitude, deg | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 30 | | | 60 | | | 90 | | | 120 | | | 150 | | | 180 | | | 210 | | | 240 | | | 270 | | | 300 | | | 330 | | | 360 |
| 23 | 24 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | 1 | | | | | | | | |
| 22 | 23 | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | | 1 | | | | | | | | | |
| 21 | 22 | | | | | | | | | | | | | | | 1 | | 1 | | | | | | 1 | 1 | | | | | | | | | | | | |
| 20 | 21 | | | | | | | | | | 1 | 1 | | 1 | | | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | |
| 19 | 20 | | | | | 1 | | 1 | | 1 | | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | |
| 18 | 19 | 1 | | 1 | | | | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |
| 17 | 18 | | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | |
| 16 | 17 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | | 1 | | 1 | |
| 15 | 16 | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | | | 1 | 1 | | 1 | | | | | |
| 14 | 15 | | | | | | | | | | | | | | | 1 | | 1 | | | | | 1 | | 1 | | 1 | | | | | | | | | | |
| 13 | 14 | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | |
| 12 | 13 | | | | | | | | | | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | 12 | | | | | | 1 | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | 11 | | 1 | | 2 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 9 | 10 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | 1 | |
| 8 | 9 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | 1 | | | 1 | | 1 | | | |
| 7 | 8 | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | 1 | | 1 | | | | | | | |
| 6 | 7 | | | | | | | | | | | | | | | 1 | | 1 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | | | |
| 5 | 6 | | | | | | | | | | 1 | 1 | | 1 | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | |
| 4 | 5 | | | | 1 | | 1 | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 4 | | 1 | | | 1 | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 2 | 3 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | 1 | |
| 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | | |
| 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | 1 | | 1 | | | |
| Totals | | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 2 | 3 | 4 | 4 | 1 | 4 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 2 | 4 | 3 | 5 | 4 | 3 | 4 | 3 | 5 | 2 | 5 | 2 | 4 | 2 |

Number of measurement opportunities

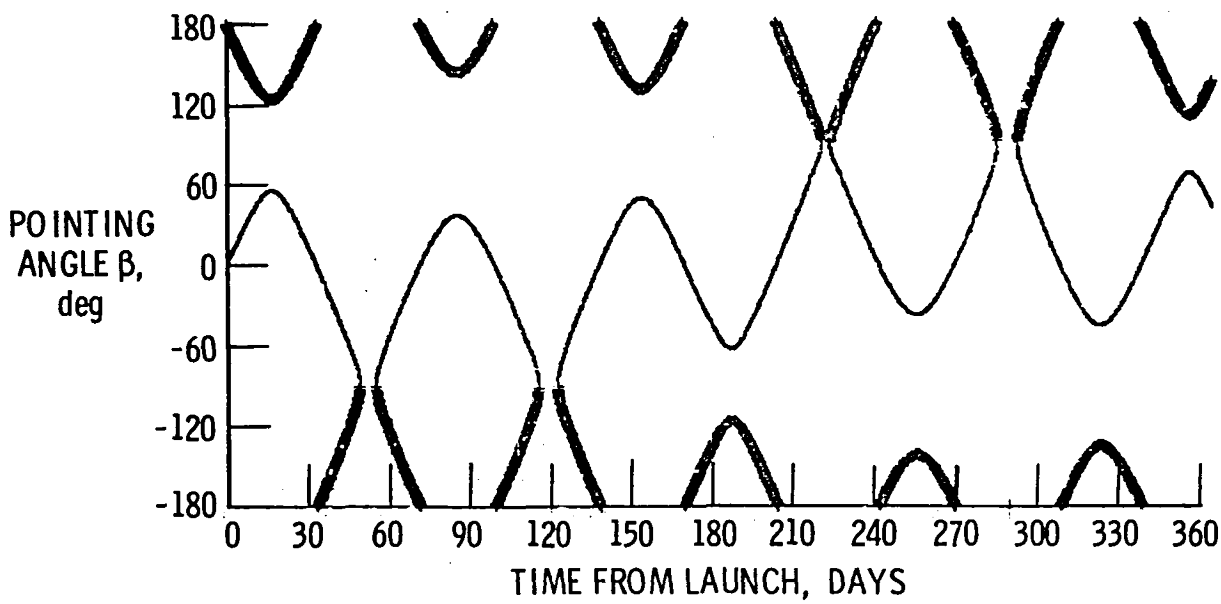
Table 7. Measurement Opportunities in the Latitude Band from 40 to 50 Degrees As a Function of Relative Solar Time (see text) and Longitude for the Nominal Dual Satellite Mission, for 30 Days.

| Relative Solar Time, hours | | Longitude, deg | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 30 | | | 60 | | | 90 | | | 120 | | | 150 | | | 180 | | | 210 | | | 240 | | | 270 | | | 300 | | | 330 | | | 360 |
| 23 | 24 | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 22 | 23 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | 1 |
| 21 | 22 | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 |
| 20 | 21 | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | 1 | | 1 | | 1 | | | | | | | | |
| 19 | 20 | | | | | | | | | | | | | | | 1 | | 1 | | 1 | | 1 | | 1 | | | | | | | | | | | | | |
| 18 | 19 | | | | | | | | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | |
| 17 | 18 | | | | | 1 | | 1 | | 1 | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | |
| 16 | 17 | | 1 | | 1 | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 |
| 15 | 16 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | 1 |
| 14 | 15 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | | |
| 13 | 14 | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | 1 | | | | | | | | |
| 12 | 13 | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | | | | | | | | | | | | | |
| 11 | 12 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | 11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | 9 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | 8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Totals | | 0 | 4 | 1 | 2 | 0 | 2 | 0 | 2 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 3 | 0 | 3 | 2 | 1 | 2 | 1 | 3 | 0 | 3 | 0 | 4 | 0 | 4 | 0 | 4 |

Number of measurement opportunities

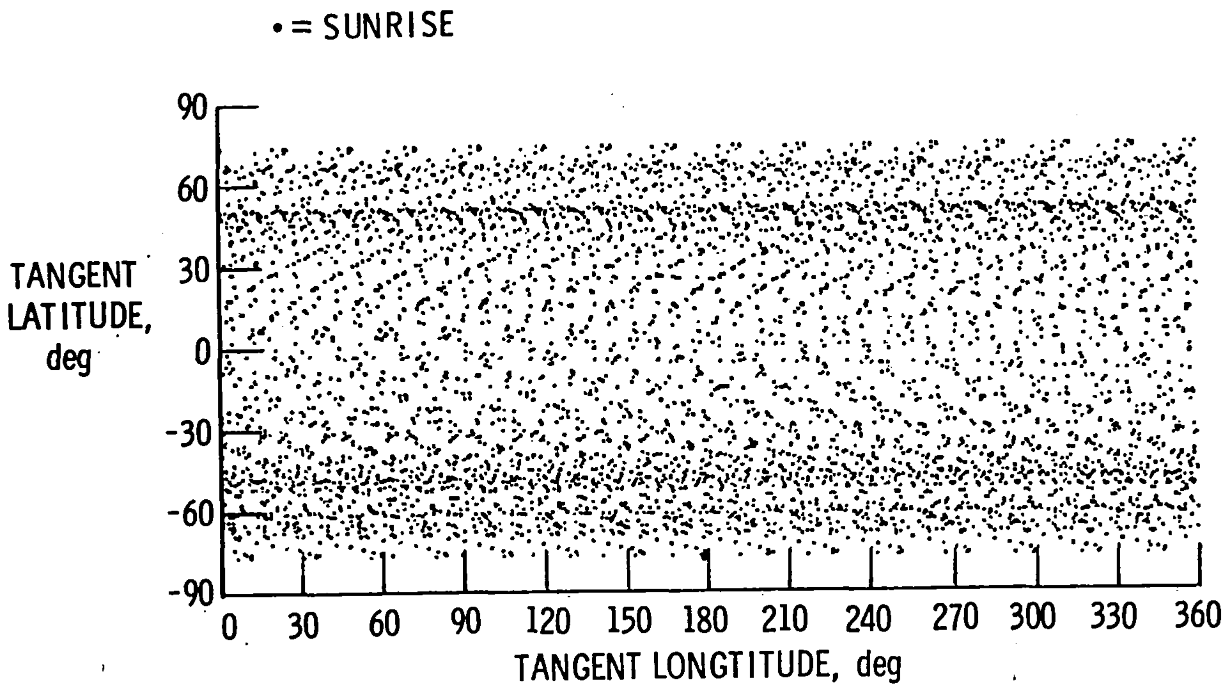



(a) tangent latitude as a function of time from launch

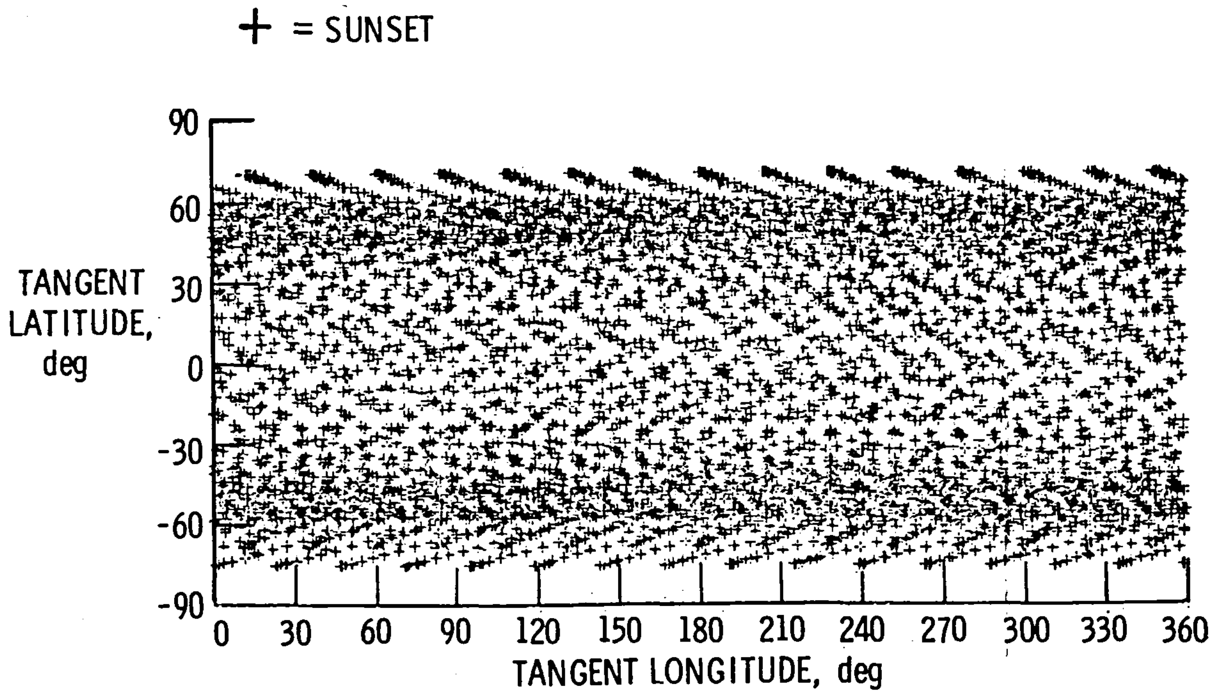



(b) pointing angles as a function of time from launch

Figure 1. Mission parameters for the nominal solar occultation mission, for 1-year.

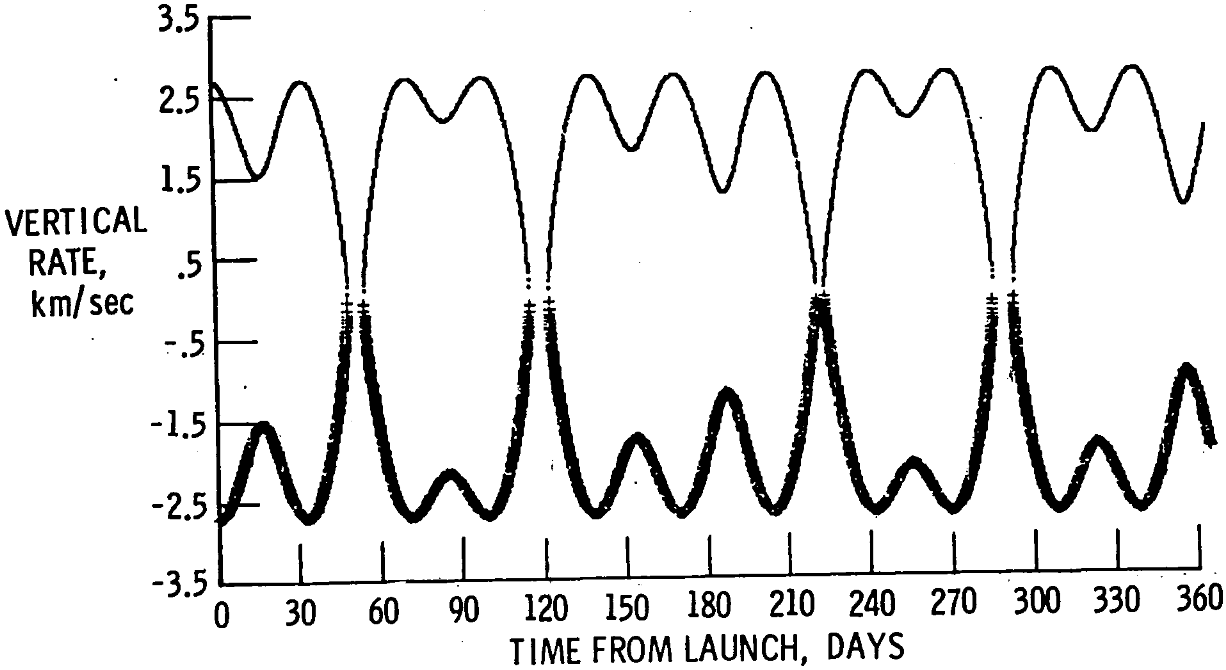



(c) tangent latitude as a function of tangent longitude for sunrises



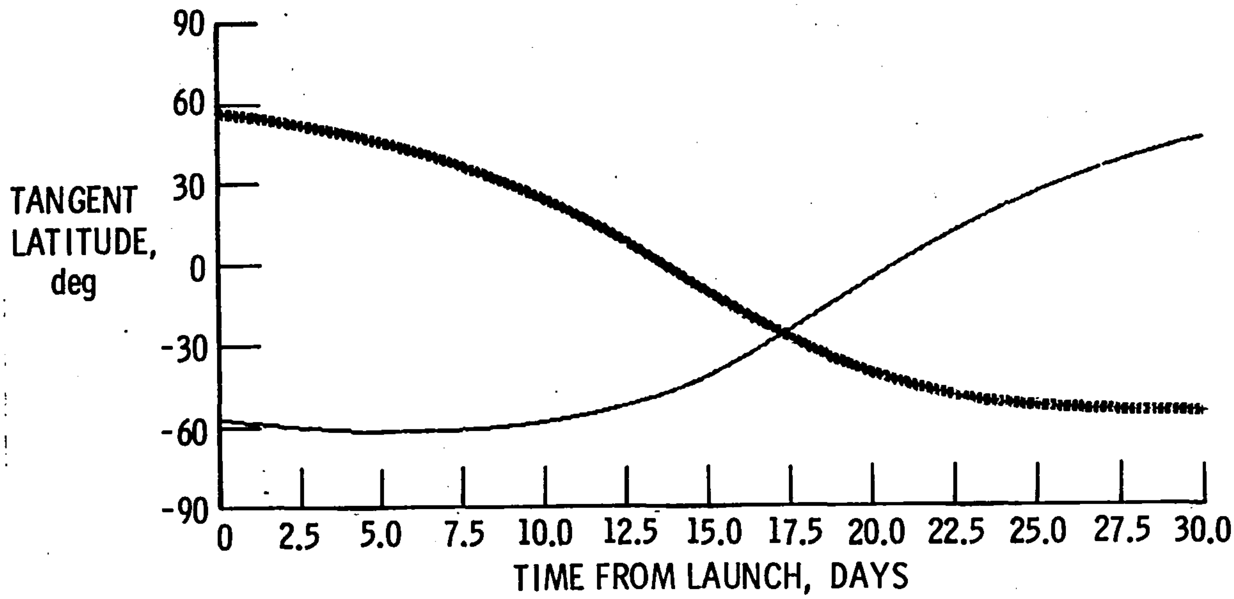

(d) tangent latitude as a function of tangent longitude for sunsets

Figure 1. (cont.)

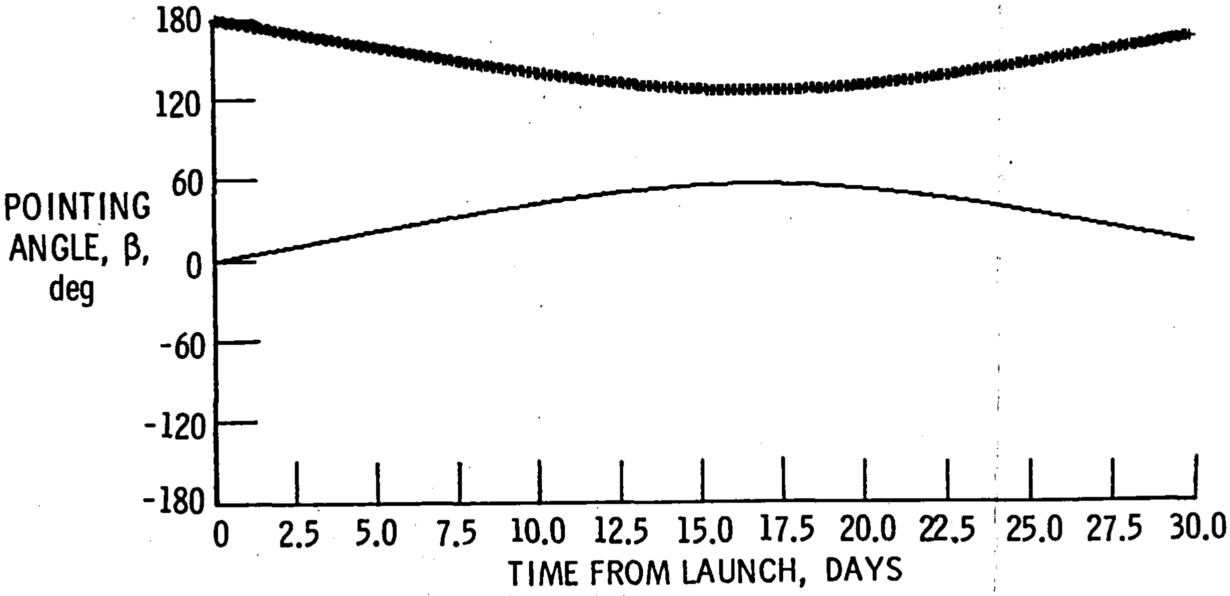



(e) apparent vertical velocity $V_{rel}$ of the Sun at the horizon

Figure 1. (conc.)

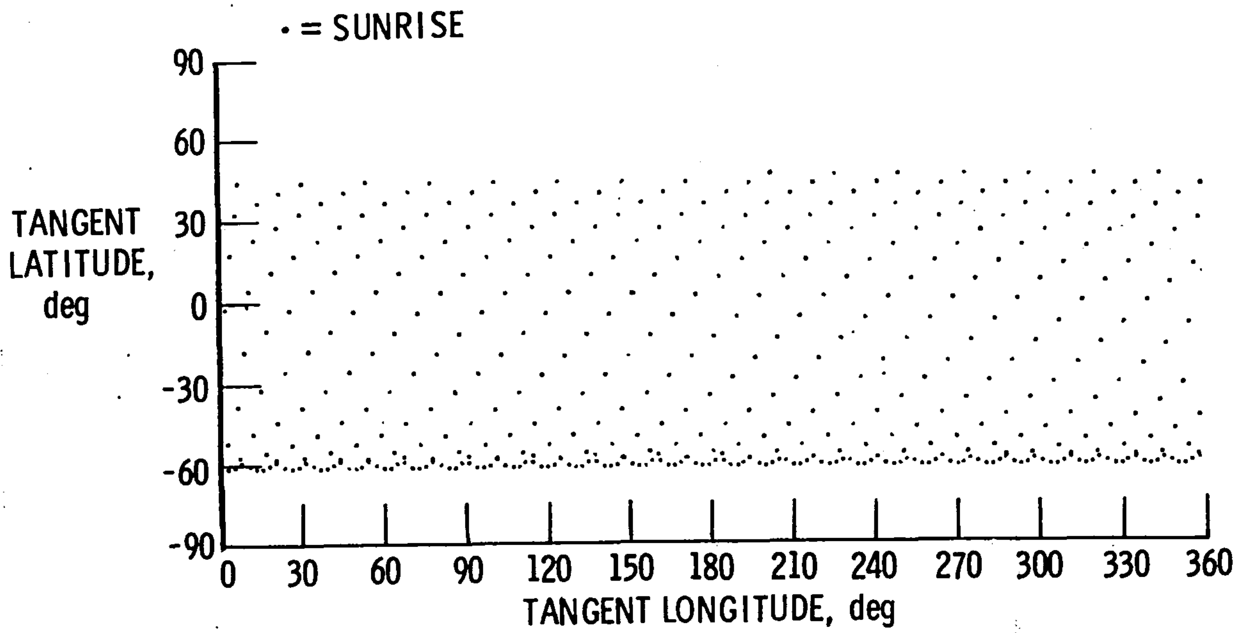



(a) tangent latitude as a function of time from launch

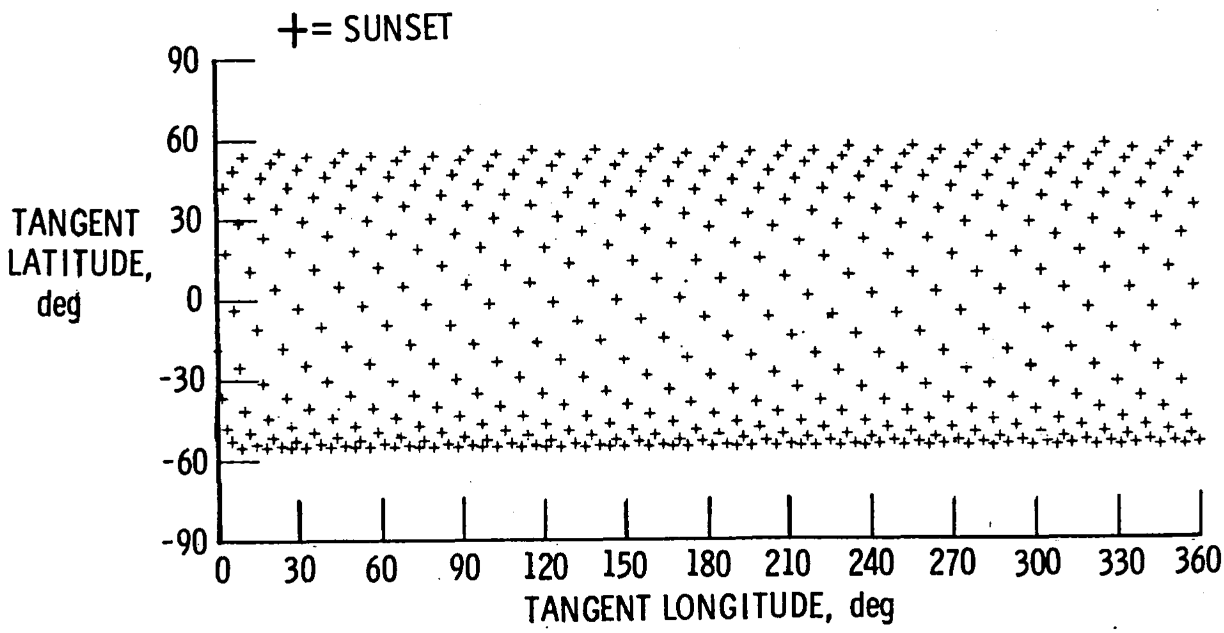



(b) pointing angle as a function of time from launch

Figure 2. Mission parameters for the nominal solar occultation mission, for 30 days.

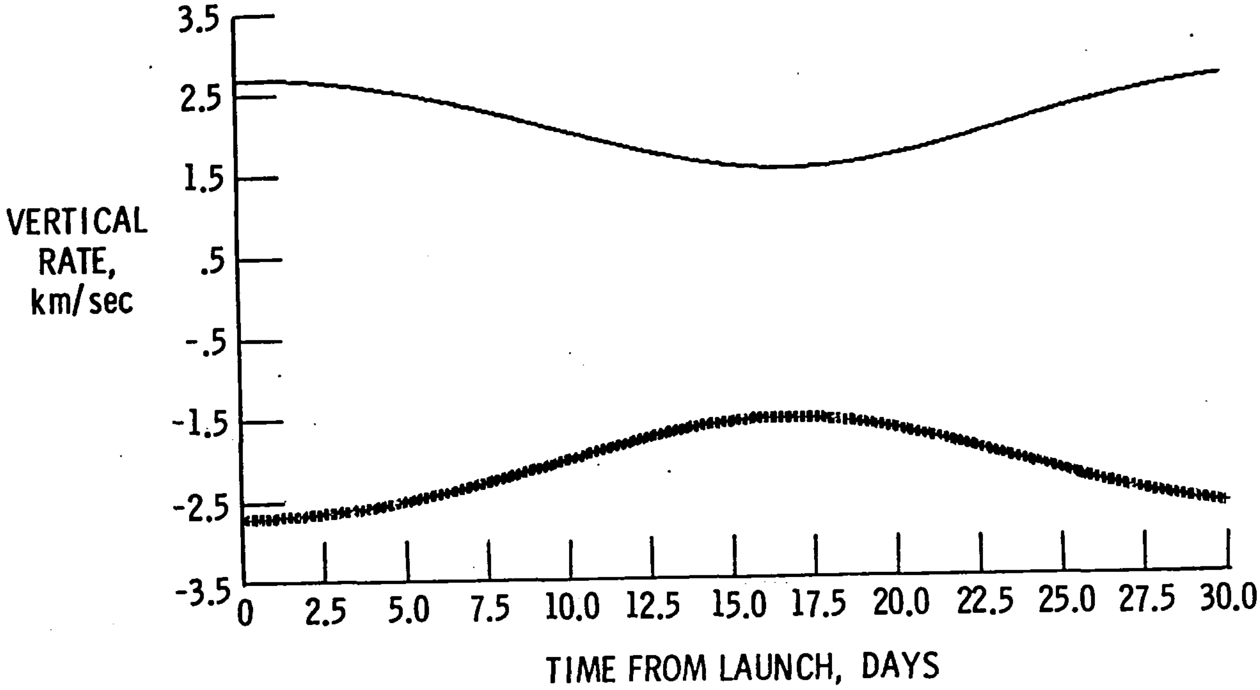



(c) tangent latitude as a function of tangent longitude for sunrises




(d) tangent latitude as a function of tangent longitude for sunsets

Figure 2. (cont.)




(e) apparent vertical velocity $V_{rel}$ of the Sun at the horizon

Figure 2. (conc.)

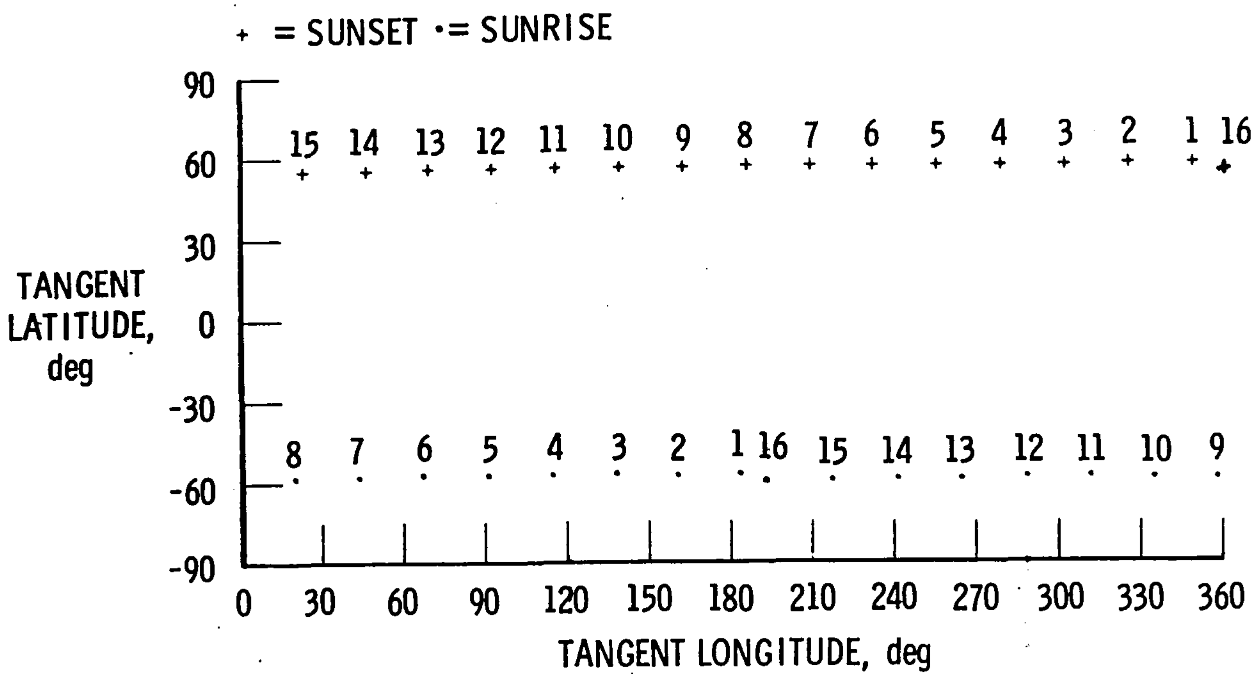



Figure 3. Tangent latitude as a function of tangent longitude for the first 16 orbits of the nominal solar occultation mission.

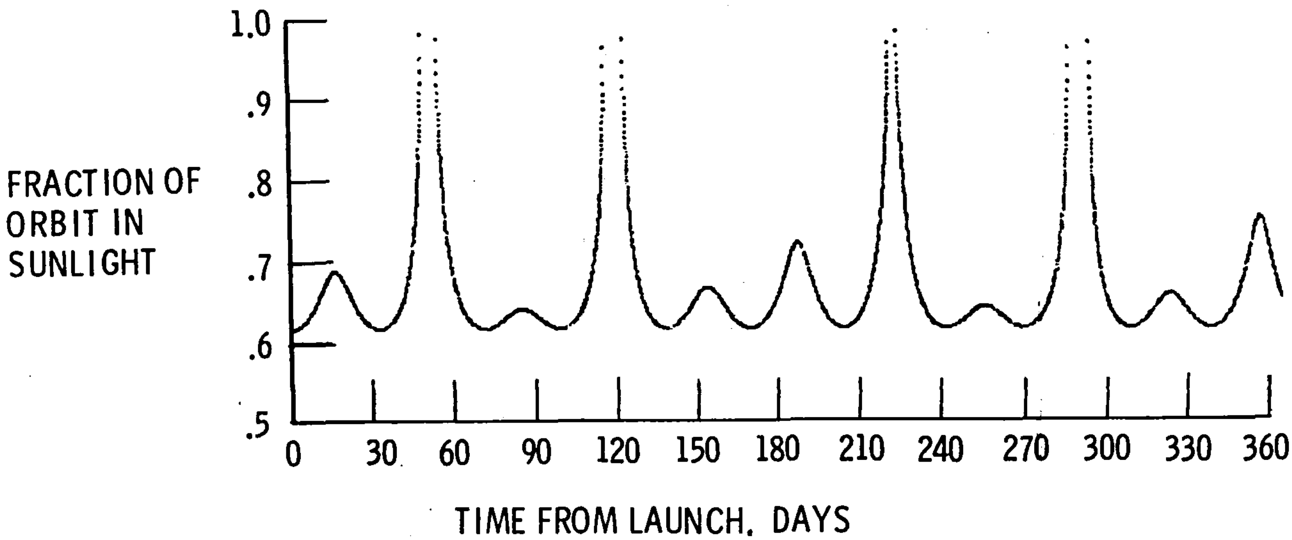



Figure 4. Fraction of an orbit spent in sunlight for the nominal solar occultation mission, as a function of time, for 1-year.

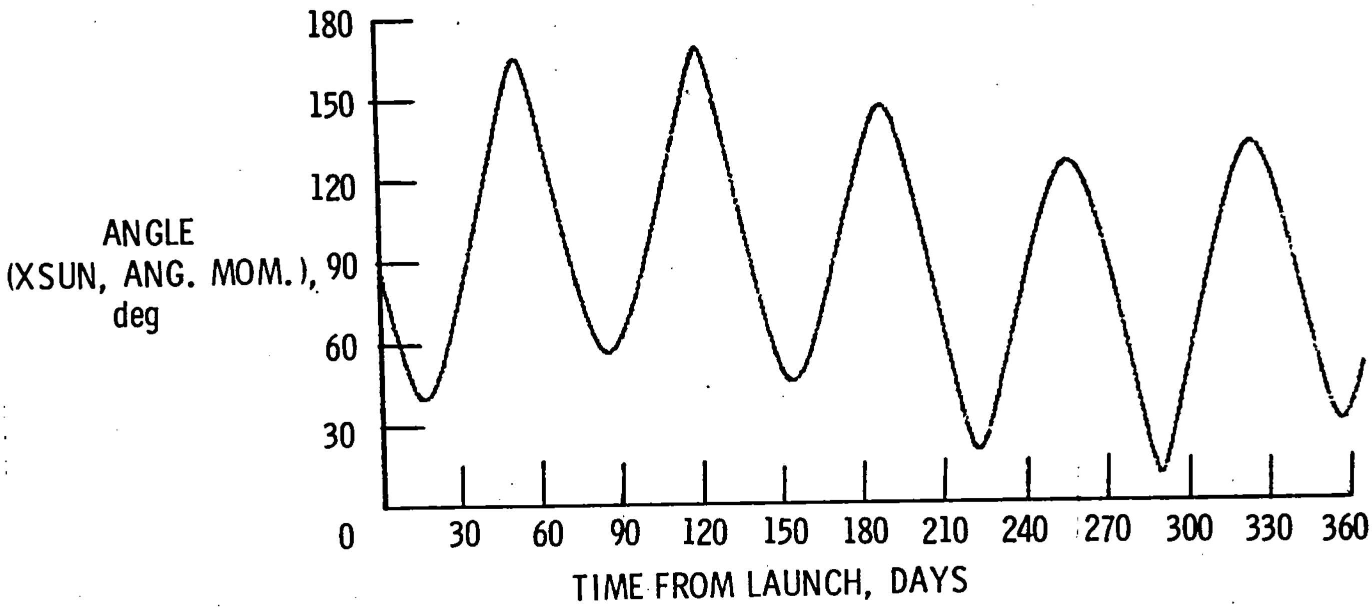



Figure 5. Angle between the unit spacecraft angular momentum vector and a unit vector to the Sun for the nominal solar occultation mission, as a function of time, for 1-year.

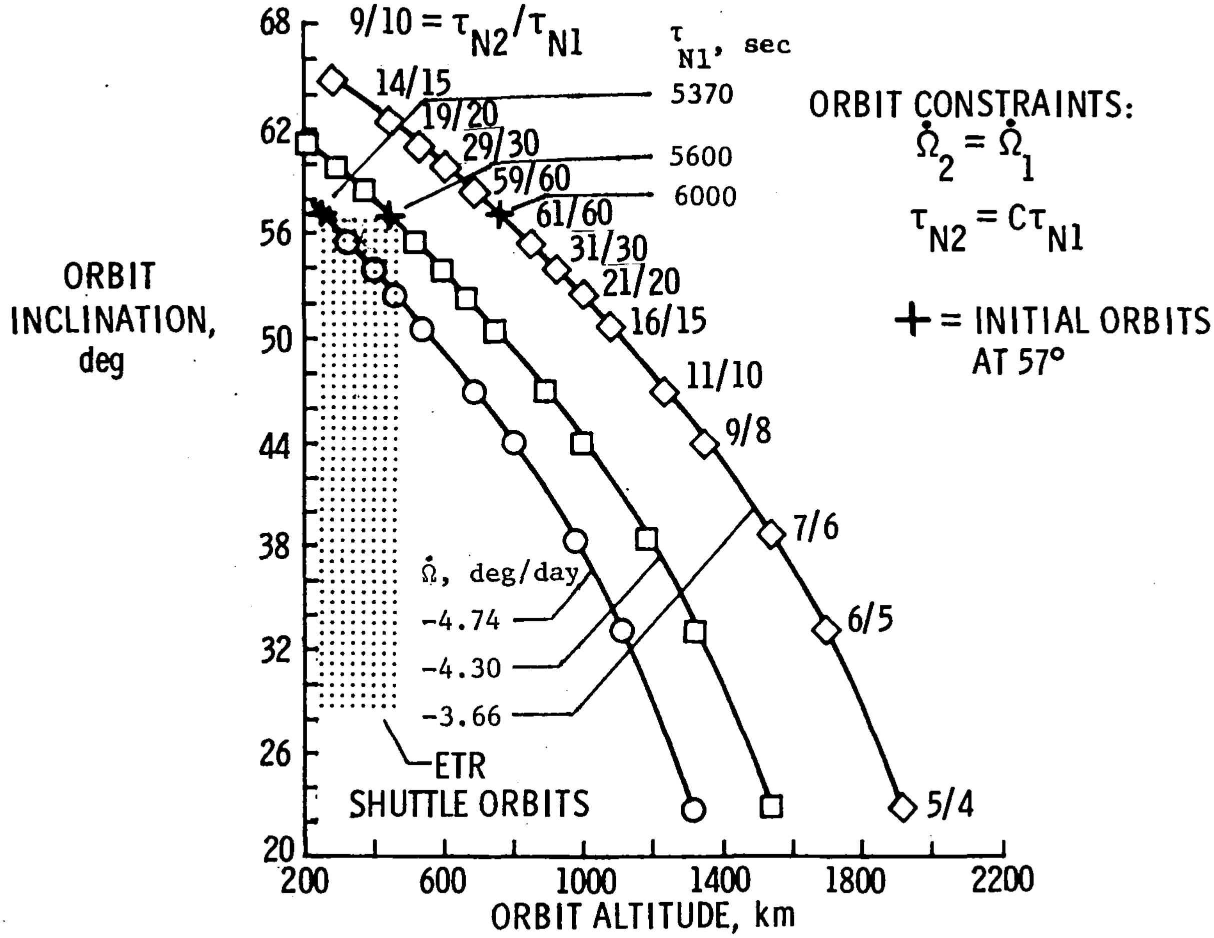



Figure 6. Orbit inclination and altitude for various dual satellite pairs: $i = 57^{\circ}$, $\tau_{N1}$ = 5370, 5600, 6000 sec.

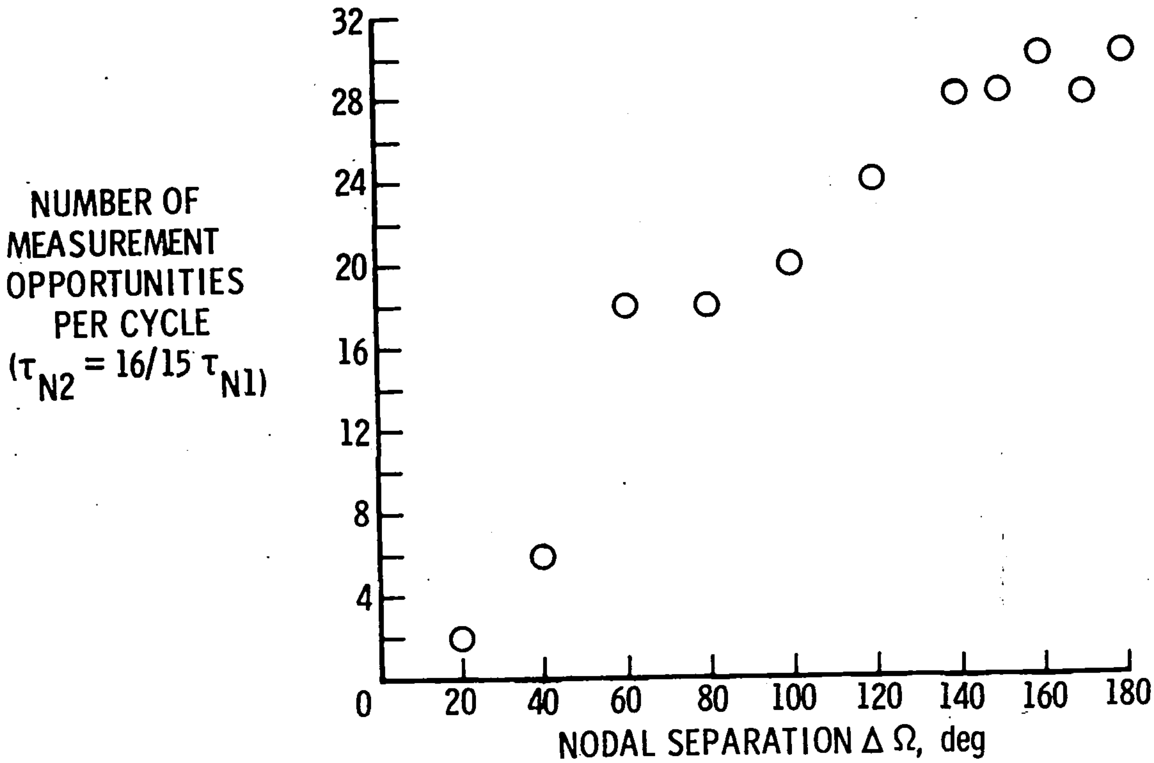
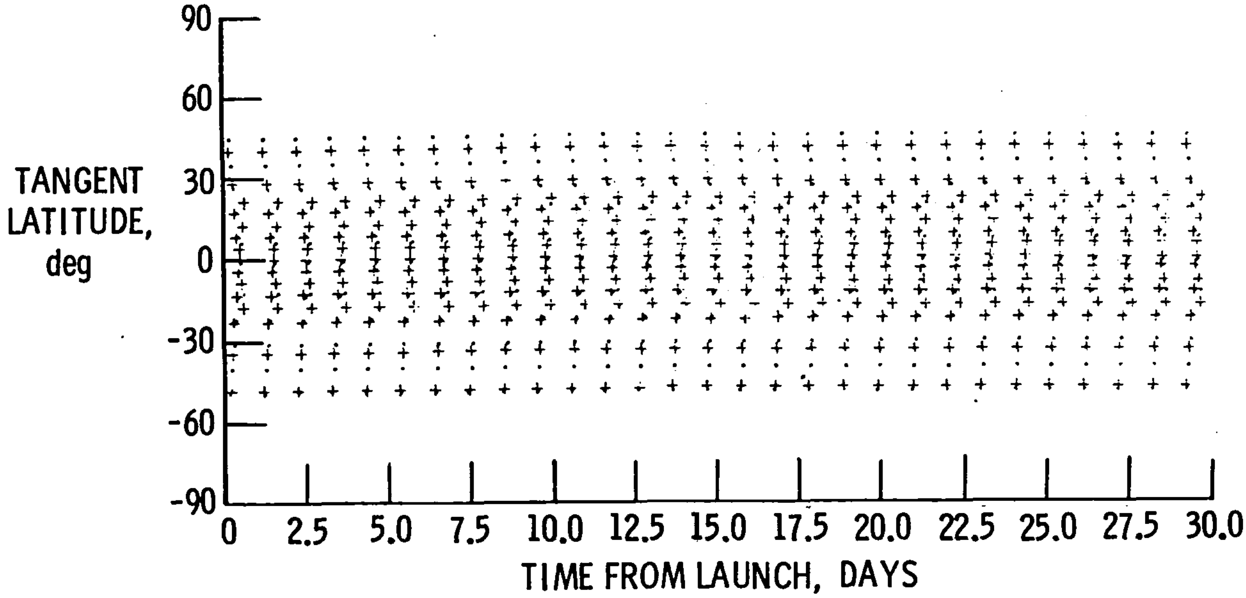
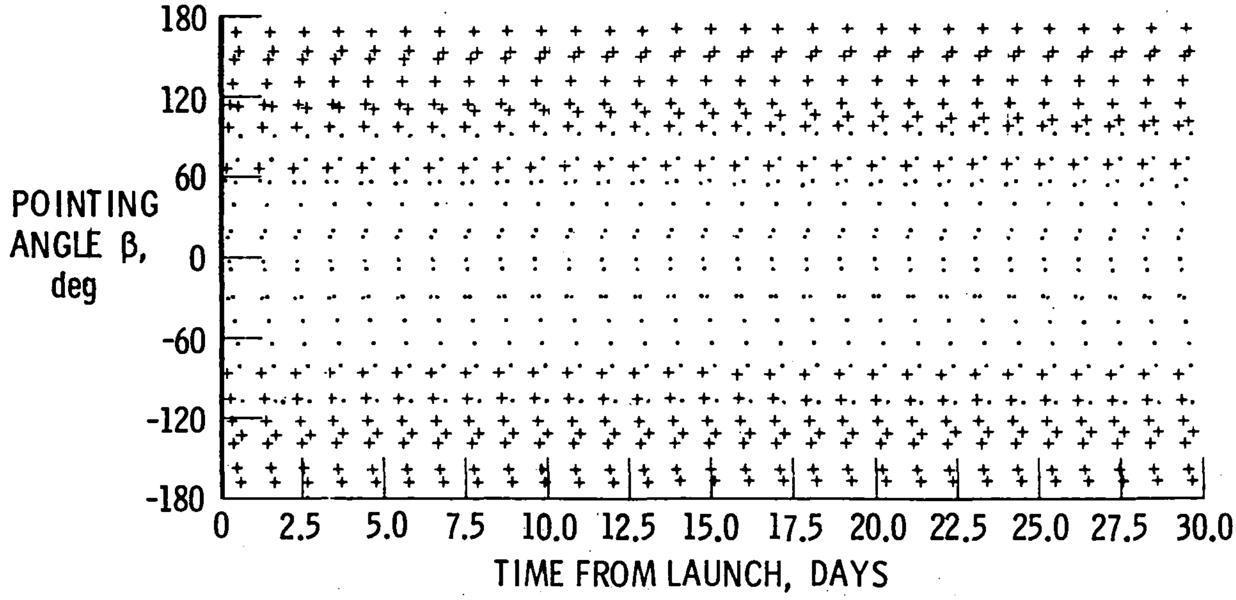



Figure 7. Number of measurement opportunities during 1 cycle of the nominal dual satellite mission (16 revolutions of the first orbit) as a function of separation between the two orbit planes

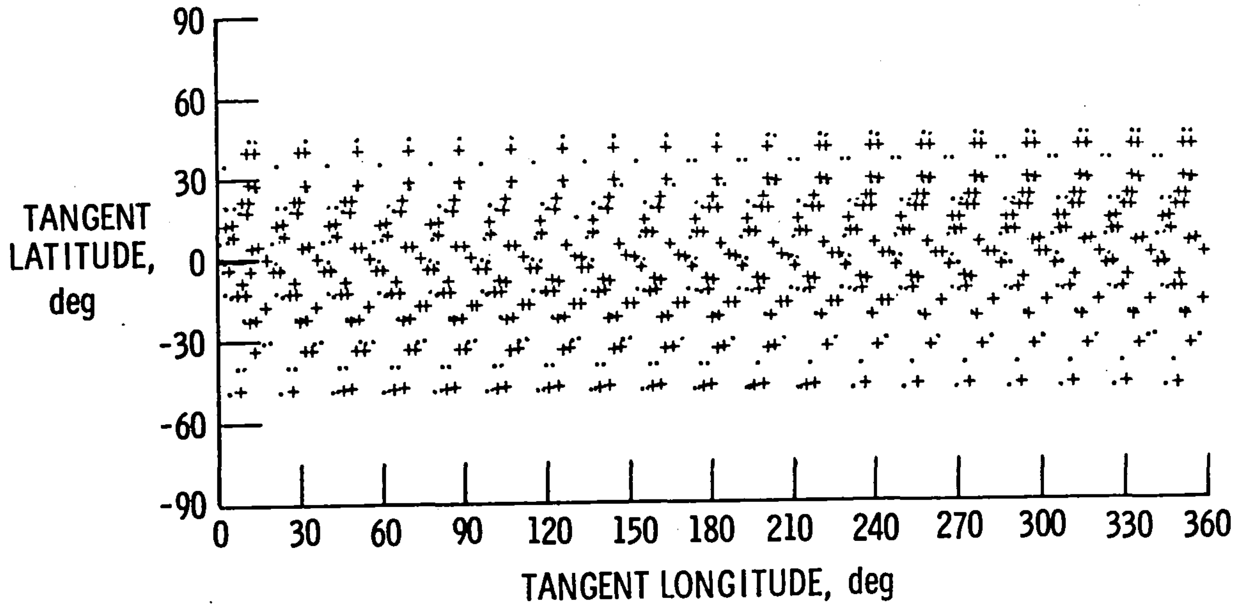



(a) tangent latitude as a function of time from launch

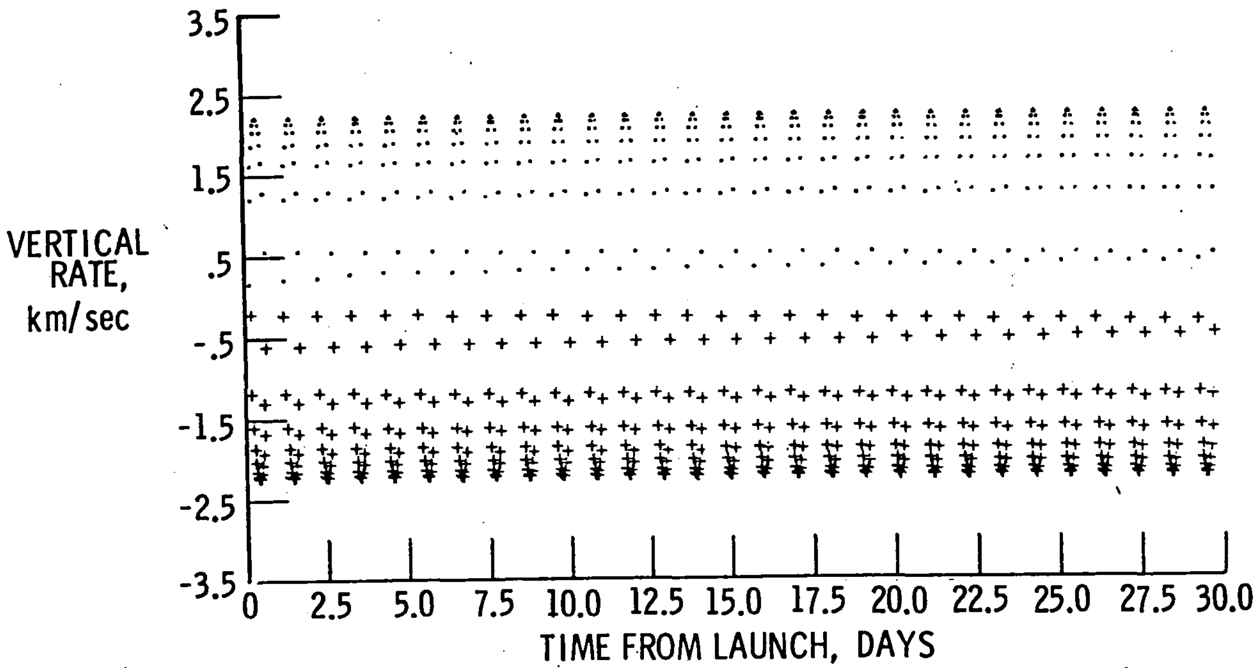



(b) pointing angle as a function of time from launch

Figure 8. Mission parameters for the nominal dual satellite mission, for 30 days.

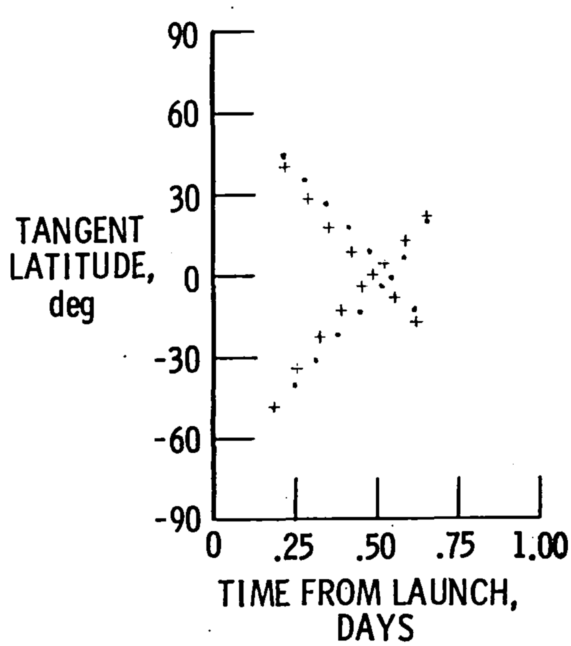



(c) tangent latitude as a function of tangent longitude

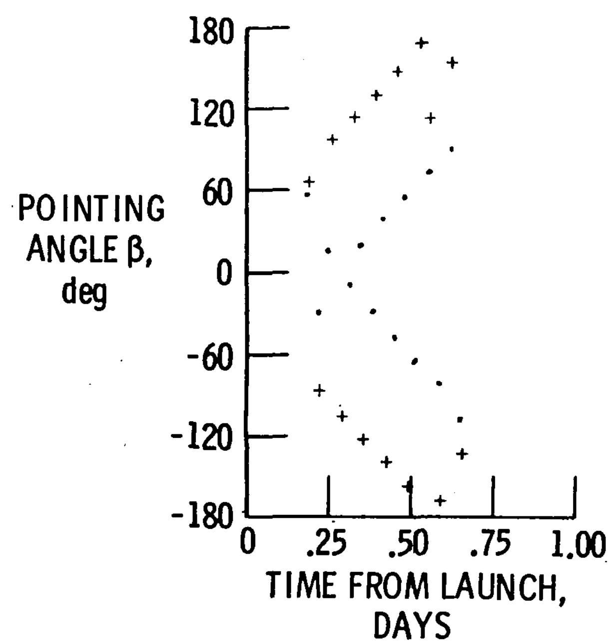



(d) apparent vertical velocity $V_{rel}$ of the satellite at the horizon as a function of time from launch

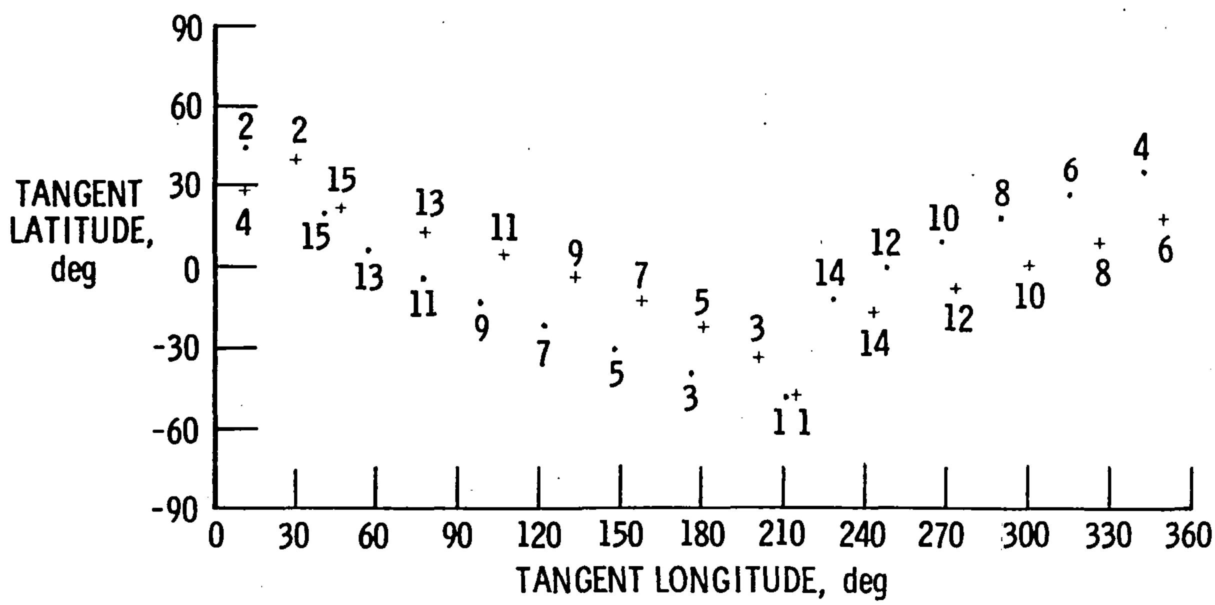
Figure 8. (conc.)




(a) tangent latitude as a function of time from launch

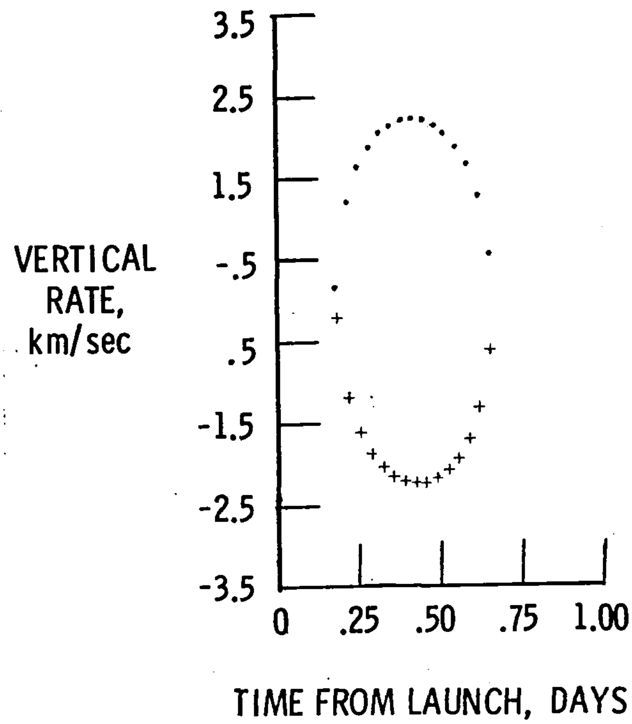



(b) pointing angle as a function of time from launch




(c) tangent latitude as a function of tangent longitude

Figure 9. Mission parameters for the nominal dual satellite mission, for 1 day.




(d) apparent vertical velocity $V_{rel}$ of the satellite at the horizon as a function of time from launch

Figure 9. (conc.)

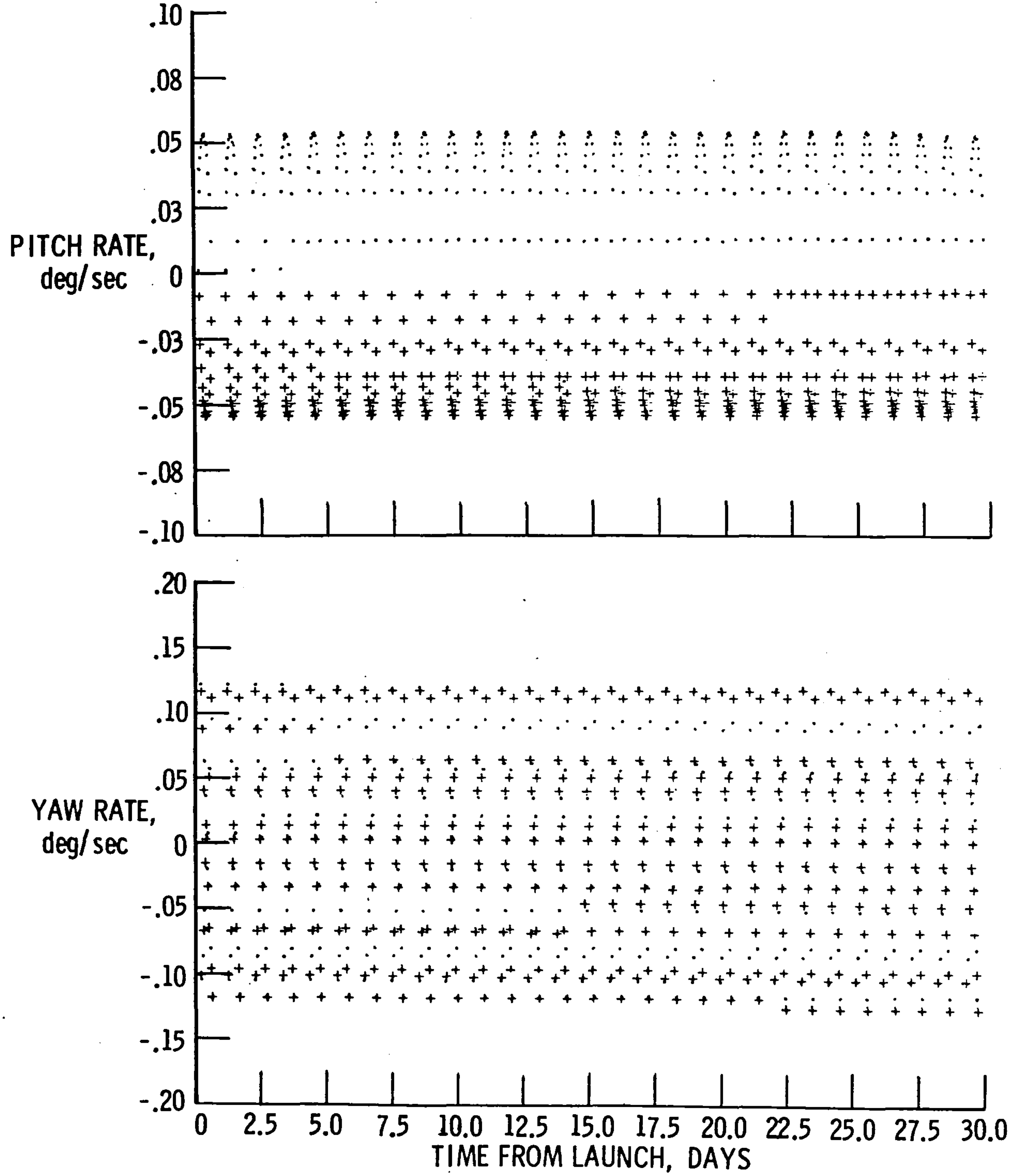



Figure 10. Pitch and yaw angle rates for the nominal dual satellite mission, as a function of time from launch, for 30 days.

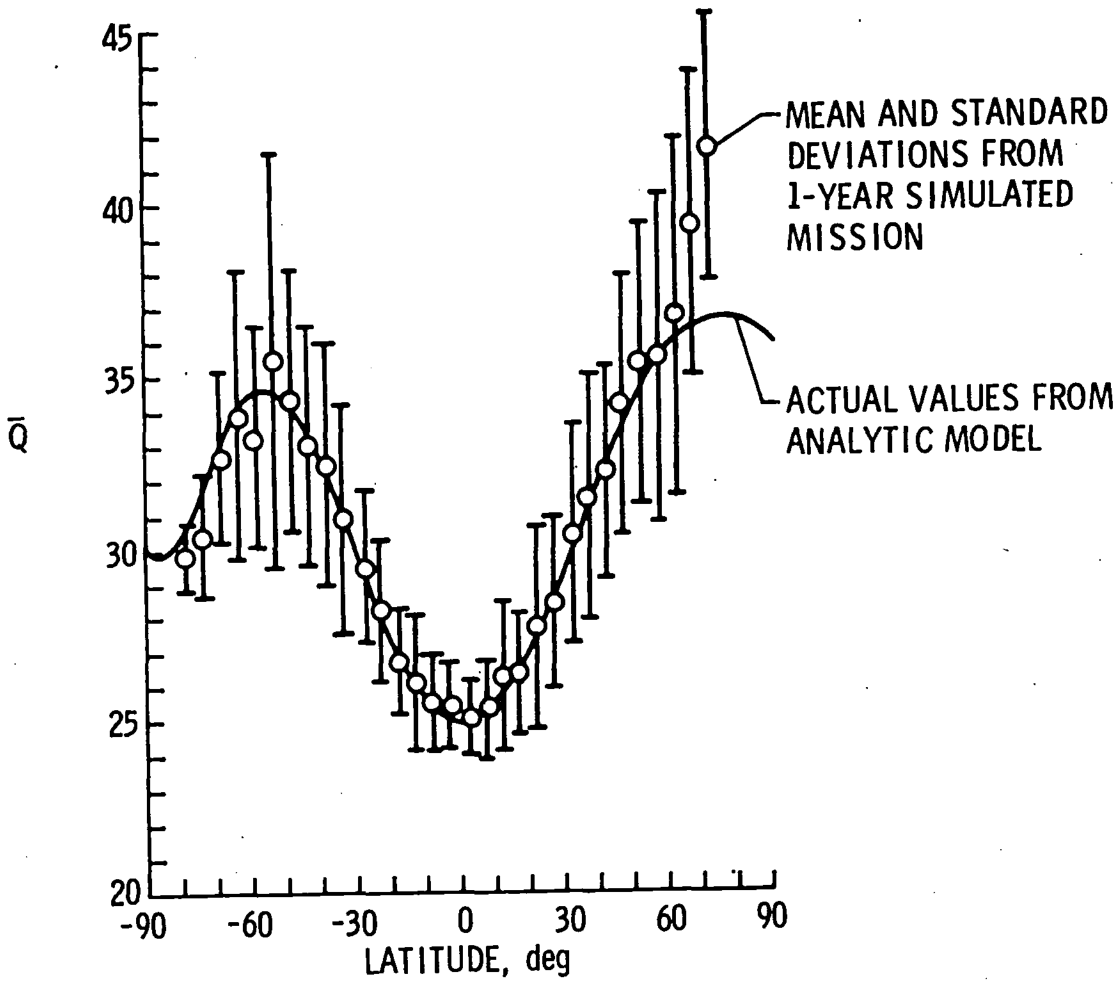



Figure 11. Yearly averages of Q as a function of latitude

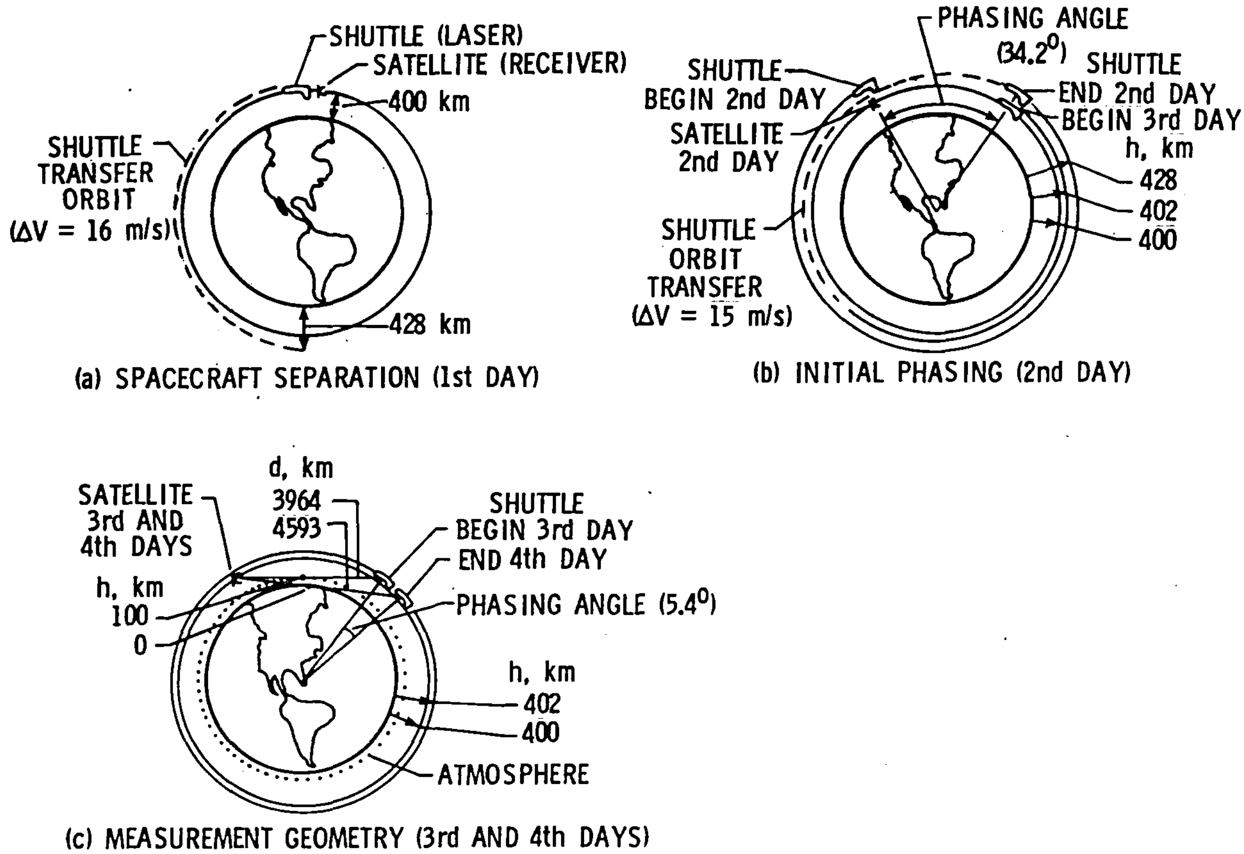



Figure 12. Phasing and orbit transfer maneuvers for a hypothetical 1 week coplanar dual satellite precursor mission.

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM-80137 | | |
| 4. Title and Subtitle<br>Orbit Design for Solar and Dual Satellite Occultation Measurements of Atmospheric Constituents | | 5. Report Date<br>July 1979 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>David R. Brooks<br>Edwin F. Harrison | | 8. Performing Organization Report No. |
| | | 10. Work Unit No.<br>146-20-14-01 |
| 9. Performing Organization Name and Address<br>National Aeronautics and Space Administration<br>Langley Research Center<br>Hampton, Virginia 23665 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered<br>Technical Memorandum |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | | 14. Sponsoring Agency Code |

15. Supplementary Notes

AIAA Paper 79-101 presented at the AAS/AIAA Astrodynamics Specialist Conference, Provincetown, Mass., June 25-27, 1979

16. Abstract

Two types of satellite-based occultation missions are considered for measuring atmospheric constituents. Nominal cases for each type are presented to demonstrate representative solutions to orbit design problems. For the solar occultation mode, large areas of the globe can be covered during a 1-year mission, but the measurements are limited to local dawn or dusk. For the dual satellite mode, with a laser aboard a second satellite to act as a source, diurnal coverage can be obtained at the expense of more complex systems and mission scenarios. In this mode, orbit pairs are selected which maintain their relative orbit plane geometry while their differing periods drive cyclic patterns of latitude coverage. A simulated 1-year solar occultation mission is used to illustrate one way of analyzing occultation data by averaging measurements within bands of constant latitude.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Earth orbit dynamics, mission analysis, atmospheric monitoring | Unclassified - Unlimited<br>Subject Category 13 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | 54 | $5.25 |

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